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EVALUATION OF ALGORITHM THRESHOLDS FOR CROP CANOPY SENSOR-BASED
IN-SEASON NITROGEN APPLICATION IN CORN

by

Brian Theodore Krienke

A THESIS

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EVALUATION OF ALGORITHM THRESHOLDS FOR CROP CANOPY SENSOR-BASED

IN-SEASON NITROGEN APPLICATION IN CORN

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University of Nebraska, 2011

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Nitrogen fertilizer is frequently the most limiting nutrient in corn production. Typically most nitrogen is applied before planting. Since nitrogen can leave the soil system fairly easily, the result can be an inefficient use of nitrogen fertilizer. Previous research has shown increased efficiency with no reduction in yield by applying nitrogen later in the season when the crop is actively growing, with rates regulated spatially through the use of active crop canopy sensors. This study evaluated the potential for N cutoff thresholds using a sufficiency index as the threshold value for areas with poor stand or an unrecoverable N deficiency. In this study the algorithm developed by Solari, et al. (2010) was used. Field scale treatments were imposed on six irrigated fields in south-central and western Nebraska to evaluate performance of the active crop canopy sensor-based in-season N management algorithm with and without predicted permanent yield loss thresholds. The study found no consistent advantage in yield, nitrogen use efficiency, or profit with sensor-based treatments using algorithm thresholds. The

uniform, soil-test-based UNL treatment was most often the most profitable treatment. Further research is needed to revise the Solari, et al. (2010) method to account for soil-N supply prior to and following in-season N application.

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Literature Review

Nitrogen is one of the most difficult to manage nutrients for a corn crop. Nitrogen exists in many forms in the soil. It can exist as the non-available form of organic nitrogen that must be mineralized by soil microbes before it can be taken up by the plant, or it can be in an available inorganic form, which can more readily be taken up by the corn plant. Nitrate (NO_3^-) is an inorganic form of nitrogen taken up by plants. It is negatively charged, which complicates its management in soil. Since it is not held by cation exchange sites in soil clays and organic matter, it can be leached with water through the soil profile and eventually to groundwater (Schilling, 2002). Typical management practices by producers today often involve applying 75% or more of the total nitrogen for a growing season before the crop is planted (Cassman et al., 2002). Scharf et al., (2002) stated that fall nitrogen application creates a substantial risk of losing nitrogen and yield. Between the time the nitrogen is applied and when the crop can actively take it up, there is opportunity for nitrogen to be lost from the soil environment due to greater exposure of nitrogen applied in the fall or at planting to a range of loss processes (immobilization, leaching, denitrification, volatilization, and clay fixation) (Scharf, 2002). This is both an economic loss for the producer in lost fertilizer and yield, but it is also an environmental concern.

Raun and Johnson (1999) indicated that world-wide nitrogen use efficiency (NUE) is only 33%. This means that 66% of the total nitrogen applied is being lost. This is mainly due to poor synchrony between soil nitrogen supply and crop

demand, as well as failure to account for temporal variability and the influence of weather on mid-season nitrogen needs (Lory and Scharf, 2003). Better management can increase NUE by synchronizing the application of nitrogen fertilizer when the crop is actively taking up N (Fageria and Baligar, 2005). Russelle et al., (1983) reported that fertilizer nitrogen accumulation per plant was greatest between the 12 leaf (V12) and silking growth stage (R1), except when nitrogen application was made at the 16 leaf stage (V16), where the maximum accumulation rates occurred during early grain fill. They concluded that improved fertilizer nitrogen use efficiency in irrigated corn often results from delaying application of moderate nitrogen rates until the crop is rapidly growing. This is essentially synchrony between application and plant growth.

Several of the past and current nitrogen recommendation strategies focused on past yield history and used the historic yield as a predictor of future yield (Meisinger and Randall, 1991). A producer would then apply a uniform rate of nitrogen fertilizer to the whole field based on the recommendation. One main drawback of this approach involves the predicted yield itself. Producers will typically pick the highest yielding occurrence in the field and extrapolate that value for the whole field (Scharf et al., 2005). Since there typically is not a yield penalty for excess nitrogen application, the fertilizer rates are generally inflated as a means of protecting yield, but not increasing it significantly either (Scharf et al., 2005). There is also an economic incentive for a producer to over-apply because there is an economic incentive to err more frequently in the direction of over application. The cost of unneeded nitrogen fertilizer in areas of over application is less than the cost

of lost yield potential in areas of under application (Scharf et al., 2005). However, we know that there is spatial variability within fields, and temporal variation due to weather from year to year (Mamo, 2003). Inman et al., (2005) stated that uniform applications within fields discount the fact that nitrogen supplies from the soil, crop nitrogen uptake, and response to nitrogen are not the same spatially. The result of applying more nitrogen than is needed to achieve the most economical yield is an environmental problem.

There has been research that looked at the spatially variable nature of fields, and tried to address the variability for nitrogen management. Ferguson et al., (2002) addressed this fact by exploring possible delineations of variability within each field. They looked at delineating management of the field based on soil organic matter content and soil nitrate, while using a uniform expected yield. Nitrogen would then be applied at different rates for these areas based on the current University of Nebraska at Lincoln (UNL) nitrogen recommendation algorithm for corn. The algorithm involved applying nitrogen based on yield history that had been adjusted upward by 10% to project future yield and then subtracting from this base rate for various factors such as: soil nitrate, organic matter content, previous legume crop, etc. (Ferguson, 2000). They concluded that applying in zones based on the UNL algorithm, which was developed as a generalized equation, probably was not appropriate for the soil and climatic situations that could arise when the algorithm was applied spatially. It should be noted that there was not a net advantage or disadvantage to this method at the time, but no evidence that this method was worth the investment of time and money to do. Scharf et al., (2005) looked at

variability in the optimal nitrogen fertilizer rates throughout a field for corn. They observed that optimum nitrogen rate could vary over or under the recommended uniform rate by as much as 34 kg/ha. They suggested that if possible, variable rate application of nitrogen could be beneficial if the optimum rate of nitrogen could be reasonably predicted spatially across a field. These studies alluded to the future practice of using spectral radiometers to measure light reflectance that responds to physiological changes within a plant.

Al-Abbas et al., (1974) observed that an excess or deficiency of an essential element, such as nitrogen, may cause visible abnormalities in pigmentation, size and shape of leaves, and the appearance of various other symptoms. Since many deficiencies can be detected visually, researchers sought to find the relationships between certain light wavelengths and specific nutrient deficiencies. Plants interact with light by absorbing certain wavelengths, scattering and reflecting others. Researchers wanted to know which wavelengths were being reflected and absorbed during a nitrogen deficiency. Blackmer et al., (1996) stated that a nitrogen deficiency reduces chlorophyll content of leaves, and chlorophyll content makes up the majority of nitrogen within a plant (Yoder and Pettigrew-Crosby, 1995). It is also directly related to the photosynthetic capacity of the plant, which can translate into yield (Schlemmer et al., 2005). It would be important to quantify the relationship between spectral reflectance, chlorophyll concentration, and nitrogen deficiency.

Spectral radiometers can be used to measure light reflectance. These passive-type sensors rely on natural illumination from the sun or an artificial light source to reflect off the plant and into the sensor, which can measure wavelengths

of light from the visible spectrum to higher wavelengths such as near-infrared and middle-infrared. Al-Abbas et al., (1974) found that reflection of visible and near-infrared wavelengths 400 to 2600 nm was influenced by the physiological age of leaves as well as plant nutrient deficiencies including nitrogen. Thomas and Gausmann, (1977) noted that reflectance in the 750 to 1300 nm range (near-infrared) is generally associated with leaf structure and morphology and not nutrient deficiencies. This is because the structure of mesophyll cells reflect the longer near-infrared (NIR) wavelengths, and plants do not utilize these wavelengths for growth (Gausman et al., 1969). Older more mature plants reflect more NIR wavelengths because there is more structure developed from the cell walls (leaf structure), which causes more scattering and reflecting of the incoming wavelengths (Jensen, 2007; Gitelson et al., 1996b).

Al-Abbas et al., (1974) showed that leaf reflectance at 550 nm was a good indicator of chlorophyll and carotenoid concentrations for eight different crops, including corn. Daughtry (2000) and Osborne et al., (2002) agreed with this finding. Differences in reflectance in the blue (450 nm) and red (670 nm) are small relative to those in the green (550 nm) wavelengths when looking at changes in chlorophyll concentration. This is because it takes a relatively small amount of chlorophyll concentration to absorb most of the blue and red wavelengths, but not green wavelengths (Gitelson et al., 1996b). Blackmer (1996) measured reflectance of wavelengths between 400-1100 nm one year and 350-1050 nm the next, over an actively growing corn canopy. Wavelengths which were the best indicators of nitrogen deficiency were centered around 550, 650, and 710 nm. Daughtry, (2000)

and Schlemmer et al., (2005) both found relationships between chlorophyll and reflectance in the red edge as well. The red-edge is defined as “wavelength of the maximum slope (maximum first derivative) of the reflectance spectrum in the 650 nm to 800 nm wavelength region” (Horler et al., 1983). It is known that an increase in chlorophyll concentration causes a broadening of the chlorophyll absorption feature in red wavelengths and consequently can move the position of the red-edge to longer wavelengths (Munden et al., 1994). Since water is known to absorb and reflect less at higher wavelengths, Schlemmer et al., (2005) attempted to isolate the confounding effect of water stress on detecting nitrogen stress. They used passive-type sensors to further elucidate the reflectance properties of chlorophyll and eliminate influence from other management factors. They found that effects due to chlorophyll content were apparent in the wavelength regions of 525 to 680 nm and 740 to 800 nm, but effects of water stress appeared in the 740 to 800 nm wavelengths. They observed that the slope of the red-edge appeared at 695 nm for low nitrogen treatments across different water treatments and at 730 nm for all water and high nitrogen treatments. This indicated that the position of the red edge was a function of nitrogen status in the plant, and not water. Individual wavelengths as described above are good indicators of a corn plant’s nitrogen nutrition,

The problem with sensing reflectance is that the relatively subtle differences in canopy reflectance associated with changes in leaf chlorophyll are often confounded with major changes in plant growth and development due to nitrogen treatments (Daughtry, 2000). Light transmittance has also been used as a tool to determine a nitrogen deficiency. Daughtry (2000) observed the correlation of leaf

transmittance and chlorophyll content. One device that measures transmittance, known as a chlorophyll meter, clamps on a corn leaf, produces its own light, and measures light transmittance in the 650 and 940 nm wavelengths. These devices are known to have a strong correlation with actual chlorophyll content (Markwell et al, 1995). Chlorophyll meter readings, which are essentially a measure of greenness, are generally linear with extractable chlorophyll concentrations for a wide variety of crops (Daughtry, 2000). Transmitted light must pass through the leaf, which increases the likelihood of this light's interaction with chlorophyll and other light-absorbing molecules (Daughtry, 2000). Reflected light, on the other hand, does not all react with leaf pigments or leaf structures; some light is reflected at the leaf surface (Daughtry, 2000).

Several researchers have utilized the chlorophyll meter as a means of in-season nitrogen management, but have also realized that the chlorophyll meter or leaf transmittance measurement is not practical on a field scale because of the intensity of sampling, time, and labor that would be needed to describe spatial trends. Walburg et al., (1982) suggested that spatial variability of nitrogen nutrition could be described using canopy reflectance sensors. Measurement of canopy reflectance allows the use of a moving platform, such as a high clearance sprayer, to move quickly through a field and receive data readings. This seemed like an opportunity to detect the variability that exists within a field that was previously not possible. Walburg et al., (1982) observed the negative influence that reflectance from soil had on trying to isolate wavelengths specific to nitrogen nutrition in a corn canopy. Soil background was found to have a drastic influence on sensing a corn

canopy at low leaf area indexes. Norman et al., (1985) explained that reflected radiation on an absolute scale is dependent on many factors, including sensor and illumination angles, canopy architecture and because the sensors were passive, solar irradiance. Blackmer et al., (1996) eliminated some of the problems with varying illumination differences by referencing data to incident or incoming radiation. To alleviate some of the influence of background reflectance from the soil and random scattering of light, indices were developed. Indices use various key wavelengths, and developing relationships among wavelengths. One such index is the Chlorophyll Index (CI) shown in Equation 1 (Gitelson et al., 2006).

Equation 1

$$\text{Chlorophyll Index (CI)} = \frac{NIR}{Green} - 1$$

The absolute reflectance values of near-infrared to green may change, but the ratio of the two under different lighting conditions is a somewhat constant occurrence within a crop species. This makes the CI ratio relative to an individual crop species or hybrid rather than absolute. This allows relative comparisons of chlorophyll concentration among the same species or hybrid. With changing light conditions, background conditions, and crop morphology, the ratio of these differences are to an effect normalized. The most widely used index is the Normalized Difference Vegetation Index (NDVI), first proposed by Rouse (1974), and referenced by Tucker (1979). This index normalized the near-infrared wavelengths with the visible red wavelengths (Equation 2).

Equation 2

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

The NDVI effectively minimizes the influence bare soil has on crop canopy measurements. Research continued to pursue both individual wavelengths that describe specific nutrient deficiencies, but also additional indices that do so, such as the NDVI.

Technological advancements have led to the development of active sensors, which produce their own light and do not need sunlight. They can be used in conditions of complete darkness. The other key benefit of active sensors is that the light generated by the active sensor is modulated to be completely distinguishable from natural sunlight (Solari et al., 2008). They provide a constant light source that does not fluctuate throughout the day or night. However, these sensors typically do not have the large range of wavelengths passive-type sensors possess. They are usually very specific in which wavelength or band they measure. Solari et al., (2008) used an active sensor Crop Circle model ACS-210 (Holland Scientific, Lincoln, NE). It measures canopy reflectance at two wavelengths (bands) in the visible centered at 590±5.5 nm and near-infrared centered at 880±10 nm. This sensor was used because it had appropriate wavelengths to be used with the Chlorophyll Index (CI) developed by Gitelson et al., (2003, 2005) as shown in Equation 3.

Equation 3

$$\text{Chlorophyll Index (CI)} = \frac{NIR_{880}}{Visible_{590}} - 1$$

This index is very sensitive in assessing chlorophyll content or greenness under moderate-to-high crop biomass compared to previous indices, such as Green Normalized Difference Vegetative Index, also developed by Gitelson et al., (1996a). Solari et al., (2008) sought to determine the relationship the Crop Circle ACS-210 readings had with those of the chlorophyll meter because as described above, canopy sensors are able to rapidly assess reflectance compared to the intensive nature of the chlorophyll meter. Solari et al., (2008) suggested that the Crop Circle ACS-210 was better suited for assessing canopy nitrogen status compared to reproductive growth due to the corn tassel interfering with reflectance from leaf surfaces. They also found that the active sensor was more sensitive in detecting nitrogen stress than the chlorophyll meter.

This research led to the development of an algorithm by Solari et al., (2010) (simplified in Equation 4) that utilized the CI and previous research of Varvel et al., (2007), who developed an algorithm for in-season N application for corn based on chlorophyll meter information.

Equation 4

$$Nrate = 317 * \sqrt{.97 - SI}$$

Their algorithm was based on a Sufficiency Index (SI). The SI (Equation 5) compared chlorophyll meter data from a high nitrogen reference strip to the rest of the field.

Equation 5

$$SI = CI_{Field} / CI_{Reference}$$

The idea was to have reflectance from the bulk field normalized against the “greenest” corn. This way the SI value would typically be below a value of 1, which indicates a nitrogen deficiency and the need for nitrogen to be applied to correct this deficiency (Solari et al., 2010). The SI basically describes the variability that exists in the field, which previously was not possible.

Introduction

Previous literature suggested the use of variable rate nitrogen application to correct deficiencies, but not to limit the extent of the deficiency. Solari’s equation (Equation 4) focused on applying N to a corn crop that had an SI value of less than 0.97. The assumption was that a more deficient plant will have a lower SI value; therefore, requiring more N to correct the deficiency. Research done by Roberts, (2009) showed that Solari’s method was successful when implemented in his research treatments. However, Roberts, (2009) observed N being applied to areas that would not increase yield significantly. These areas included severely nitrogen stressed plants, as well as areas of low plant population, and waterways. Further research is needed to look at the effects of limiting N application on progressively deficient plants. It is thought that there is a point (SI value) at which no additional yield can be captured by applying any additional N. A threshold would also mean N savings. For the Roberts, (2009) study between two sites, N rates were simulated for threshold values from SI values of 0 to 1 in steps of .05 (Figure 1).

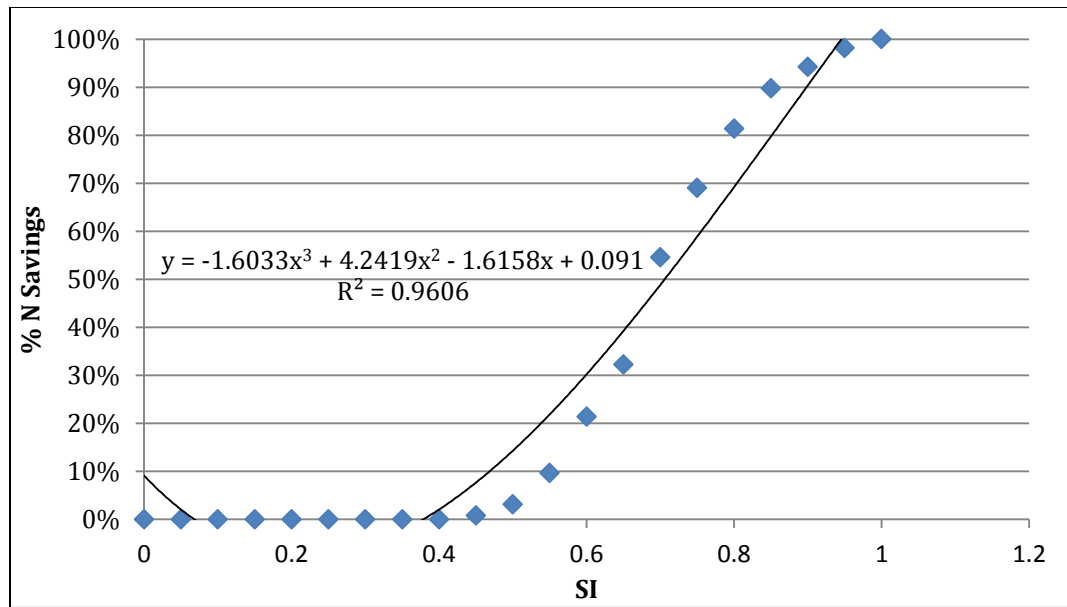


Figure 1: Percent of N not applied (saved) as a result of imposing a threshold at different SI values, and the resulting regression equation for this relationship.

If the SI value was less than this threshold SI value or greater than a SI value of 0.97, no nitrogen would have been applied. The average rate of N was then determined, which would be lower than the sensor treatment. Savings of nitrogen was calculated and compared to having a no threshold imposed treatment (sensor treatment). Consistent results occurred with all replications in both sites despite contrasting soil properties. The two fields represented fine and coarse-textured soils for as wide of a contrast as possible. Between the two sites, six different sensor treatment strips were analyzed. Relationships of nitrogen savings versus SI values were similar for both sites.

The occurrence of areas where a threshold may need to be imposed is thought to be low, but by successfully implementing a threshold, the approach by Solari, (2010) would be further refined and more efficient.

Objective

The objective of this study was to illustrate performance of the active crop canopy sensor-based in-season N management algorithm with and without imposing permanent yield loss thresholds using a series of field-long strip trials.

Materials and Methods

Site Locations and Description

The research in this study was performed on six different cooperating producer's fields over the course of two growing seasons, 2009 and 2010. Three field sites were used in 2009: Sites 09BR, 09HU, and 09RA. Three different field-sites were used in 2010: Sites 10BR, 10HU, and 10LE. The hybrid selection and other management factors for each field are shown in Table 1. Soil series and nutrient data are shown in and

Table 3 respectfully. Treatments received the same management as the rest of the field except for the nitrogen (N) management, which were altered based on treatment.

Table 1: Producer practices for each site.

	2009		
	09BR	09HU	09RA
Corn Hybrid	Pioneer 32T84	Dekalb 65-63VT3	Pioneer32B11
Previous crop	Soybeans	Yellow Corn	Soybeans
Tillage	No-Till	Strip-Till	No-Till
Row Spacing	.76 meters	.76 meters	.76 meters
	2010		
	10BR	10HU	10LE
Corn Hybrid	Pioneer 33D47	Excel 5995YGVT3	Dekalb DKC 5259
Previous crop	Soybean	Popcorn	Corn
Tillage	No tillage	No tillage	No tillage
Row Spacing	.76 meters	.76 meters	.76 meters

Table 2: Soil series and taxonomic class arranged by site.

Site 09BR		
Series	Taxonomic Class	% Trt Area
Ipage loamy fine sand 0 to 3%	Mixed, mesic Oxyaquic Ustipsamments	45.2%
Thurman loamy fine sand 0 to 2%	Sandy, mixed, mesic Udorthentic Haplustolls	22.3%
Novina sandy loam rarely flooded	Coarse-loamy, mixed, superactive, mesic Fluvaquentic Haplustolls	19.3%
Thurman loamy fine sand 2 to 6%	Sandy, mixed, mesic Udorthentic Haplustolls	13.4%
Site 09HU		
Series	Taxonomic Class	% Trt Area
Hastings silt loam 0 to 1%	Fine, smectitic, mesic Udic Argiustolls	55.7%
Hastings silt loam 1 to 3%	Fine, smectitic, mesic Udic Argiustolls	22.5%
Hastings silty clay loam 3 to 7% eroded	Fine, smectitic, mesic Udic Argiustolls	21.7%
Site 09RA		
Series	Taxonomic Class	% Trt Area
Hord silt loam 1 to 3%	Fine-silty, mixed, superactive, mesic Cumulic Haplustolls	48.1%
Thurman fine sandy loam 2 to 11%	Sandy, mixed, mesic Udorthentic Haplustolls	22.1%
Hastings silt loam 0 to 1%	Fine, smectitic, mesic Udic Argiustolls	17.5%
Hord silt loam rarely flooded	Fine-silty, mixed, superactive, mesic Cumulic Haplustolls	11.0%
Uly silt loam 3 to 6%	Fine-silty, mixed, superactive, mesic Typic Haplustolls	1.2%

Table 5 continued: Soil series and taxonomic class arranged by site.

Site 10BR		
Series	Taxonomic Class	% Trt Area
Libory loamy fine sand 0 to 3%	Sandy over loamy, mixed, superactive, mesic Oxyaquic Haplustolls	49.4%
Valentine fine sand 3 to 9%	Mixed, mesic Typic Ustipsamments	26.2%
Valentine fine sand 9 to 24%	Mixed, mesic Typic Ustipsamments	24.4%
Site 10HU		
Series	Taxonomic Class	% Trt Area
Hastings silty clay loam 7 to 11% eroded	Fine, smectitic, mesic Udic Argiustolls	43.5%
Hastings silt loam 1 to 3%	Fine, smectitic, mesic Udic Argiustolls	34.0%
Hastings silt loam 3 to 7% eroded	Fine, smectitic, mesic Udic Argiustolls	22.5%
Site 10LE		
Series	Taxonomic Class	% Trt Area
Satanta loam 3 to 6%	Fine-loamy, mixed, superactive, mesic Aridic Argiustolls	41.8%
Bayard very fine sandy loam 1 to 3%	Coarse-loamy, mixed, superactive, mesic Torriorthentic Haplustolls	23.7%
Satanta-Dix complex 3 to 9%	Fine-loamy, mixed, superactive, mesic Aridic Argiustolls	19.7%
Bankard loamy sand channeled, frequently flooded	Sandy, mixed, mesic Ustic Torrifluents	14.8%

Table 3: Select soil fertility mean values for each site.

Site	pH	OM (%)	Bray-P1 (ppm)	NO₃⁻ (ppm)
09BR	7.00	1.20	15.50	-
09HU	6.00	3.00	22.90	-
09RA	6.60	3.00	36.40	-
10BR	6.70	1.51	19.21	7.32
10HU	5.86	3.28	28.75	13.55
10LE	7.01	2.32	20.30	1.93

Treatments

Treatments were placed in each producer's field to balance the need for spatial variability to express treatments with the producer's need for practicality within their operation. Each experimental site included five field-long strip treatments in 2009 and six treatments in 2010, with three replications for each treatment in a randomized complete block design (RCBD). The strips were either 8 or 12 rows wide depending on the producer's harvesting width. Treatments in 2009 included: threshold set at a value of 0.65 sufficiency index (SI), threshold set at a value of 0.75 SI, sensor, reference, and UNL nitrogen algorithm. The treatments will be referred to as T65, T75, sensor, reference, and UNL respectfully. In 2010 a third threshold treatment with a value of 0.55 SI (T55) was added; all the other treatments remained the same.

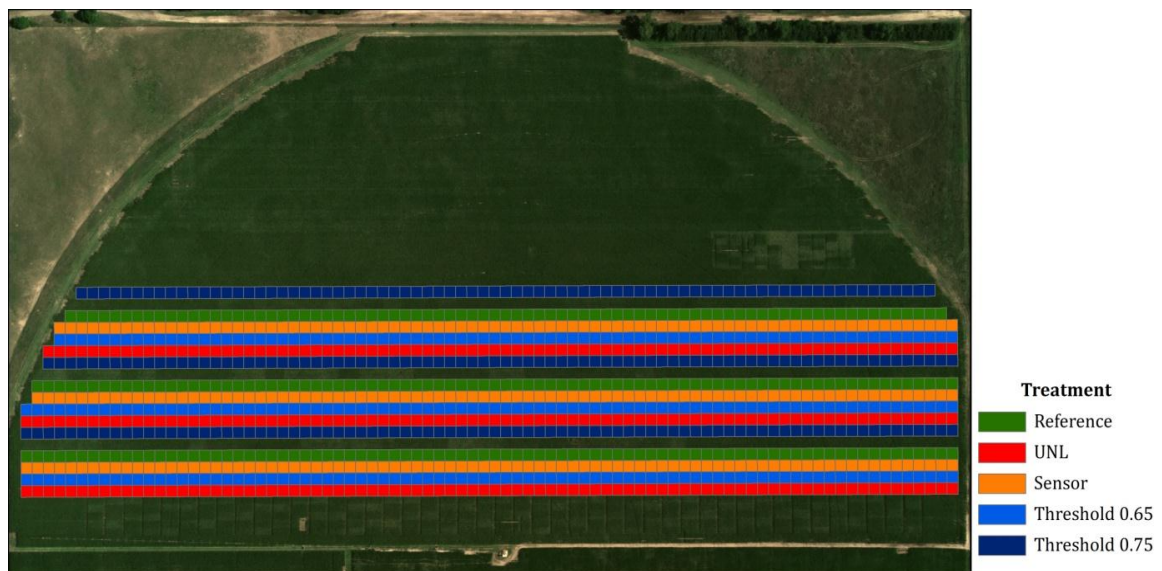


Figure 2: Treatment layout for field BR09. Treatments are overlaid on a true-color image.

The UNL treatment refers to the algorithm developed at the University of Nebraska-Lincoln for producers in Nebraska applying a uniform rate of nitrogen on a whole field basis. The algorithm (Equation 6) accounts for different sources of N, other N credits from legume crops, manure, and nitrate from irrigation water.

Equation 6

$$35 + (1.2 * EY) - (8 * NO_3^{-1} ppm) - (.14 * EY * OM) - other credits$$

The reference strip is a uniformly applied high rate nitrogen strip to ensure nitrogen is not a yield-limiting factor. The reference strip received adequate amounts of N, so as not to be limiting during sensing operations. The reference strip is the foundation for active sensor treatments, which will be explained in greater detail below.

The sensor treatment refers to a variable rate approach for applying nitrogen using crop-canopy sensors. The three different threshold treatments are variations of the same method used in the original sensor treatment.

Implementing the Sensor Treatments

The sensor-based treatment has the ability to vary the rate of nitrogen (N) application spatially via a crop-canopy sensor with associated software and hardware. The Holland Scientific ACS-210 Crop Circle active canopy sensor (Holland Scientific, Inc., Lincoln, NE) was used to determine the crop N status. This active sensor has its own light source that is modulated from that of the sun, so the sensor will only detect reflectance from its own light source instead of background radiation from sunlight or other light sources. Each sensor was calibrated by the manufacturer using a proprietary universal 20% reflectance panel with the sensor placed in the nadir position over the panel. The ACS-210 sensor measures

reflectance in two different wavelengths (bands). One band is in the visible electromagnetic spectrum centered at 590 ± 5.5 nm. The other band is in the near infrared (NIR) portion of the spectrum located centered at 880 ± 10 nm. These two bands are combined to create the Chlorophyll Index (Gitelson et al., 2003, 2005) by dividing the NIR band over the visible band and subtracting 1 from that ratio (Equation 3).

The CI is utilized in conjunction with the high nitrogen reference treatment. Before any N application, sensor readings are collected from each replication of the reference treatment. To acquire reflectance measurements, two ACS-210 sensors were mounted on a high clearance sprayer at a distance of 0.8 to 1.5 meters above the crop canopy. Each sensor was placed over the second row off the center of the sprayer on either side. In an 8 row treatment strip one sensor was placed over row 3 and the other sensor over row 6. In a 12 row treatment strip the sensors were placed over rows 5 and 8. The sensors were placed in a nadir position covering a sensing area of 0.1 by 0.5 meters with the long dimension perpendicular to the row during data collection.

A LabView-based (National Instruments Corp., Austin, TX) data acquisition and control program along with a program developed in Microsoft Visual Basic (Microsoft Corp., Redmond, WA) was used to log the data and control the output of the fertilizer applicator. During each pass over the reference treatment, the sensors recorded the CI at a 20 Hz sampling rate. One CI value for each replication of the reference strip was obtained by averaging the values sampled previously to create a

reference CI for the individual replication. The reference CI was then used as the denominator in calculating SI (Equation 7).

Equation 7

$$SI_{\text{Sensor}} = CI_{\text{Treatment}} / CI_{\text{Reference}}$$

The numerator for calculating SI is $CI_{\text{Treatment}}$. This is the CI sensed over the bulk area of the field or in the case of this study, the separate treatments. The SI indicates how relatively deficient in chlorophyll the treatment area is compared to the reference. An SI value of less than one indicates a chlorophyll deficiency, while an SI value greater than one, indicates the target crop provides a higher CI than the reference. Theoretically CI content is directly related to nitrogen content. Solari et al., (2010) utilized this relationship and developed an algorithm to produce a rate of nitrogen that could be varied throughout a field or treatment. This “nitrogen algorithm” shown below in Equation 8 is used in conjunction with the ACS-210 sensor.

Equation 8

$$N \text{ rate} = 370 * \sqrt{0.97 - SI_{\text{Sensor}}}$$

Threshold Concept

According to the nitrogen algorithm of Solari, et al. (2010), N is applied below a sufficiency index (SI) of 0.97. The current practice of using the current N algorithm approach presented an opportunity to explore whether N application was warranted at lower SI values. Hypothetically, if a lower SI value is observed, then the chlorophyll concentration is lower, which means the need for more nitrogen. The lower the SI value the higher the application rate of nitrogen. At what point does

more deficient corn (lower SI) not recover yield enough to justify applying the extra nitrogen? The threshold treatment utilized this question by cutting off any N below the threshold SI value, but above the threshold SI value, the treatment functioned the same way as a sensor treatment.

Deriving the Threshold SI Values

Roberts (2009) found that often the lowest SI values present in any of the treatments were around 0.40 to 0.45, and went up to an SI value of 1. In some cases the SI value reached values greater than 1. This range of SI values was used to determine the threshold treatments. If a cutoff or threshold SI value of less than 0.45 were used, it would essentially be testing the sensor treatment. If SI values do not drop below, 0.45, and the threshold cutoff value is set at 0.45, there would not be any points in the treatment at which the nitrogen rate would be cutoff (threshold imposed). Since values less than 0.45 typically do not exist, 0.65 and 0.75 were chosen as starting points to test threshold values. . Values were chosen because of the potential savings in nitrogen not applied that could be realized (Figure 1), as well as past experience of visual nitrogen deficiencies at these SI values. Two values allowed a good reference of whether the chosen SI values were either set too high or too low for the first year in the study. For the 2010 summer growing season one additional threshold treatment, T55, was added, which was at a SI value of 0.55. This was added after analyzing the data for 2009. The data suggested that the threshold values were not set low enough when looking at the yield and economic results. As a result, the third threshold was chosen as the midpoint between the previous lowest threshold of 0.65 and the approximate low point in SI values that were experienced

throughout the treatments, 0.45. The rest of the treatments imposed during the 2010 growing season were the same as 2009.

Treatment Application

The sensor and threshold treatment strips received 84 kg ha⁻¹ of nitrogen early in the growing season when the corn was around the third leaf stage (V3), while the reference and UNL treatments received their respective total N rate except for Sites 09BR and 10BR where applications were limited to 84 kg ha⁻¹ and 112 kg ha⁻¹ for the UNL and reference treatments respectfully. These treatment strips would not receive another application of nitrogen until the corn reached the eleventh leaf stage (V11). At V11 the sensors were used to acquire the reference strip CI. The treatments that did not receive a uniform nitrogen application then utilized the nitrogen algorithm in conjunction with the reference CI. Those treatments included the sensor, T55, T65, and T75. The UNL and reference treatments received an additional uniform rate of nitrogen to reach the recommended rate for each. Sites 09BR and 10BR received the remaining N at this stage.

Machinery Capabilities

Nitrogen was applied via a three-wheeled John Deere high clearance sprayer that had been specially customized with the ability to change rates rapidly. The applicator nozzles were controlled by an electronic solenoid valve that receives a control signal from software input. The ACS-210 Crop Circle sensors make measurements at 20 Hz. The software averages the 20 data points into one SI value,

which was done to smooth out the sensor measurements. The averaged SI value is georeferenced with the last sensor reading in array of numbers that goes into the average. Each SI value received a rate of nitrogen within the possible range of the applicator. The sensor measurements, calculated SI, and nitrogen application occurred in real time as the sprayer drove through the treatment strip at approximately 7.7 km/hr. The applicator had a valve system capable of activating any combination of three nozzles every other furrow, which allowed for eight nitrogen rates. The software calculated rates were virtually infinite; therefore, there was disparity between what was called for by the N algorithm and what was physically possible to apply. A calculated nitrogen value would fit between two applicator possible rates, unless the software called for a rate higher than the applicator could achieve. The actual rates as applied are listed in Table 4.

Table 4. The nitrogen algorithm rate is the nitrogen rate calculated from the nitrogen algorithm; the actual rate applied is what the machine does when the calculated rate is between the values on the left. The sprayer valve combination is how the machine achieves the actual rate by turning on the valve numbers listed.

2009 Growing Season Possible Sprayer Nitrogen Application Rates		
Nitrogen Algorithm Rate (kg/ha)	Sprayer Valve Combination	Actual Rate Applied (kg/ha)
0	0	0
>0-8.92	1	22.3
>8.92-31.22	2	44.6
>31.22-53.52	1&2	66.9
>53.52-75.82	3	89.2
>75.82-98.12	1&3	111.5
>98.12-120.42	2&3	133.8
>120.42	1&2&3	156.1

The rates differed in 2010 in an attempt to better represent the calculated rate. The calculated and applied rates are in Table 5.

Table 5. The nitrogen algorithm rate is the nitrogen rate calculated from the nitrogen algorithm; the actual rate applied is what the machine does when the calculated rate is between the values on the left. The sprayer valve combination is how the machine achieves the actual rate by turning on the valve numbers listed.

2010 Growing Season Possible Sprayer Nitrogen Application Rates		
Nitrogen Algorithm Rate (kg/ha)	Sprayer Valve Combination	Actual Rate Applied (kg/ha)
>0-8.92	0	0
>8.92-26.76	1	17.84
>26.76-44.6	2	35.68
>44.60-62.44	1&2	53.52
>62.44-80.28	3	71.36
>80.28-98.12	1&3	89.2
>98.12-115.96	2&3	107.04
>115.97	1&2&3	124.88

Data Analysis Methods

To analyze the results several different datasets provided by different machines had to be combined. Nitrogen rates applied from the N applicator software outputted comma separated value (.csv) files, which contained calculated rates of N, SI values, CI values, and location coordinates. The .csv files were used in ArcMap 10.0 (ESRI, Redlands, CA) for geoprocessing and analysis.

Yield data was collected by cooperating producers. Each producer had their own yield monitoring system, which logged the yield data points.

Table 6. The site and the accompanying yield monitoring system associated with yield data collection.

Site	Yield Monitoring System
09BR, 10BR, 09RA	Ag Leader (AgLeader Technology, Inc., Ames, IA).
09HU, 10HU, 10LE	John Deere GS2 (Deere and Co., Moline, IL)

The difference in individual yield monitoring systems was a source of error that cannot be accounted for, so relative differences within each site were compared instead of across sites. The yield monitor systems were calibrated according to the individual manufacturer's specifications. Yield data that was received from each producer was cleaned by utilizing YieldEditor (Sudduth and Drummond, 2007; USDA-ARS, Columbia, MO) for data filtering. Harvested weight was adjusted to a standard moisture content of 155 g kg⁻¹. The same parameters for each field were used for consistency. Data that was beyond three standard deviations was removed. Yield data was then imported into ArcMap.

In ArcMap a square polygon grid the size of the producers combine head width was created utilizing the "Create Fishnet" tool in ArcMap. The grid allowed for the yield and N application data to be joined. This served as a common scale for analyzing data, and to eliminate some of the problems with latency that are inherent with yield monitoring systems by averaging several yield points into a common grid cell. Processed data was exported into a data table that could be imported into SAS 9.2 (SAS Institute Inc., Cary, NC) for statistical analysis.

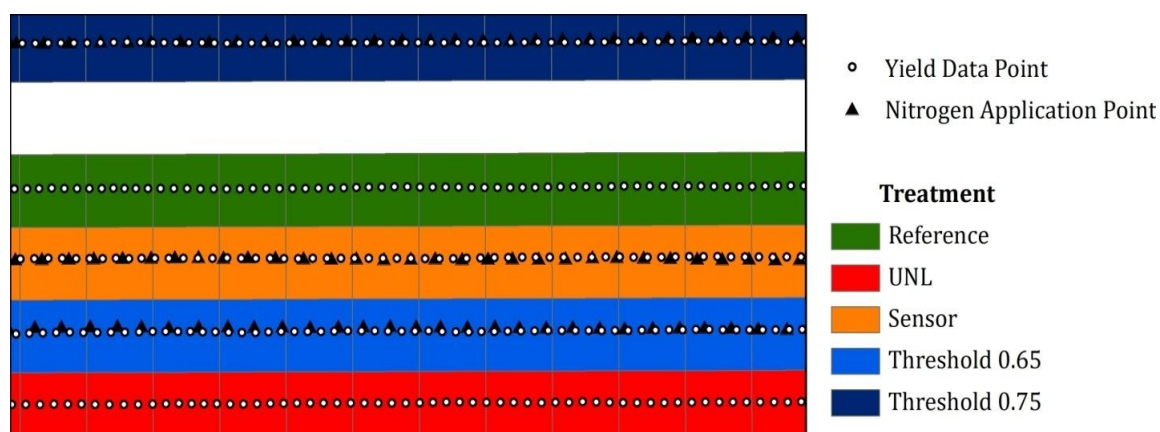


Figure 3: Representation of N application points and yield data points overlaid on 9.14 meter wide grid cells for each treatment.

Duncan Multiple Range Tests were performed using the PROC GLM in SAS 9.2 to determine significant differences between variables including yield and N rate. Initial analysis evaluated means for the entire treatment strip across all reps referred hereafter as field length strip means. The strip means included all yield and N data points for the length of the treatment strip in one value. For a threshold treatment this meant averaging both locations where the threshold was and was not imposed together. Since a common grid scale was utilized, individual points in the field at which the threshold treatment was imposed did not exist. In order to look at the individual imposed points, a subset was created from the initial point data. For each field, yield data was denser than nitrogen application data. Yield data was spatially joined via ArcMap with the N application points to place all data on the same spatial scale. A spatial join attached the attributes associated with each georeferenced N application point to the closest yield data point. After achieving a common scale utilizing point data instead of grid, the data were queried to separate only the points at which the threshold treatment was imposed. The result was a much smaller subset of yield points within the threshold treatment strips. It was assumed that the surrounding treatments for each individual replication, where the threshold was imposed, had similar spatial variability. This was due to the short distance from each treatment to the next treatment. In doing so, the spatial variability component could be taken out of the analysis, which greatly simplified data analysis. To get a representative sample of data points of when the thresholds were imposed, yield points were selected that occurred only within the imposed threshold location. Since the nitrogen application points were coarser (fewer points

per linear distance than the yield points) (Figure 3), one N application point would have directly influenced several yield points. Yield points were selected from half way between the outside of the outer imposed threshold application point to the outside of the other outer imposed threshold application point (Figure 4). Selections were half way between the point or contiguous points because each N application point represents the center area of application along the row, so the area was from the middle of one point to another. To compare against other treatments, yield points were selected in the same manner from the surrounding treatments.

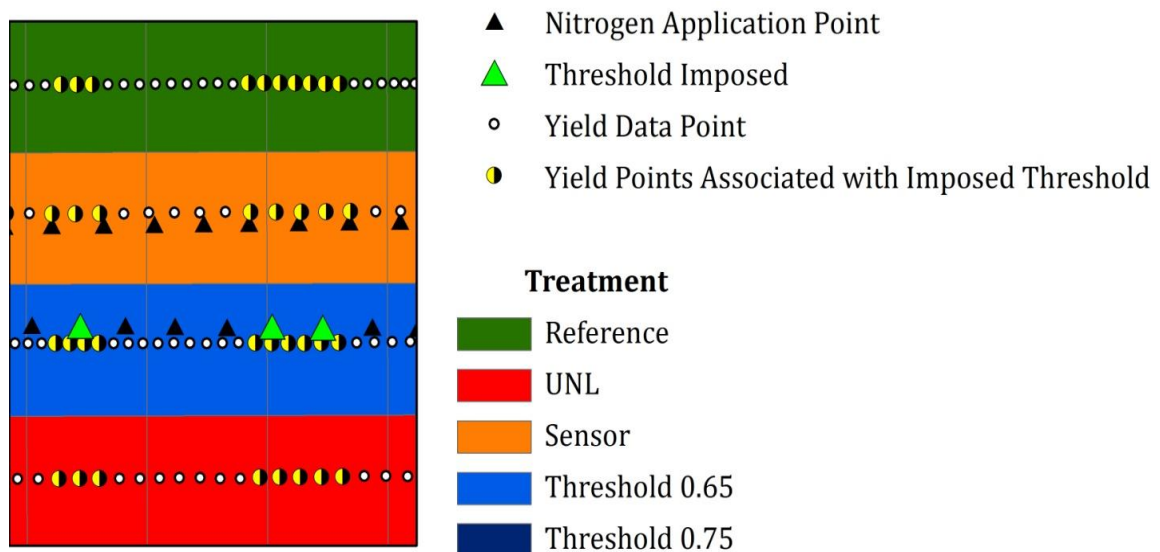


Figure 4: An example of the points that were selected that were within the imposed threshold area. Original data points for N and yield (black and white symbols respectfully) are shown with the subset data points (yellow and black symbols) overlaid. The threshold imposed symbols were the actual location where the threshold SI value was imposed.

The goal was to only evaluate one threshold against the other treatments, but there were several occurrences when the different threshold treatments were imposed within the same area. This led to overlap of yield points that were associated with both threshold treatments. To preserve associations with either threshold, unique

identifiers were given to each yield point. This allowed an individual threshold treatment or combined threshold treatments statistics to be computed. An example of one of these occurrences appears in Figure 5 below.

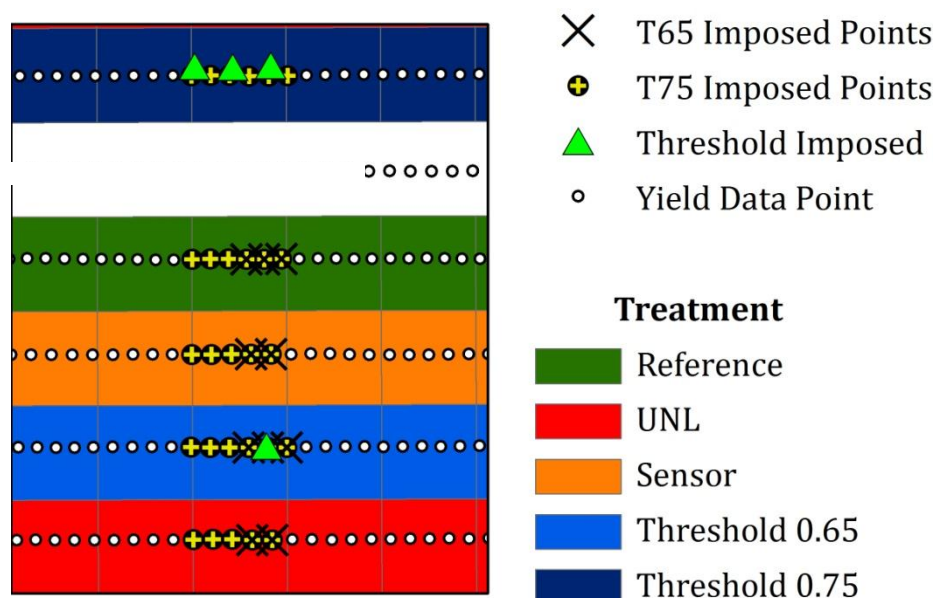


Figure 5: This is an example of how both threshold treatments were imposed in the same area. The corresponding data points from other treatments would be associated with both thresholds if unique identifiers were not created to separate the associations.

The collection of all threshold imposed data points from all the threshold treatments will be referred to as combined imposed threshold locations. Data points separated based on what threshold treatment occurred will be referred to as “individual T##” replacing the ## with the SI value of the threshold treatment of interest (T55, T65, or T75).

Results and Discussion

2009 Grain Yield Response

Field Length Strips-Grain Yield

In 2009 each site had unique responses to treatments. The reference treatment for Site 09BR yielded statistically higher than all other treatments (Figure 6).

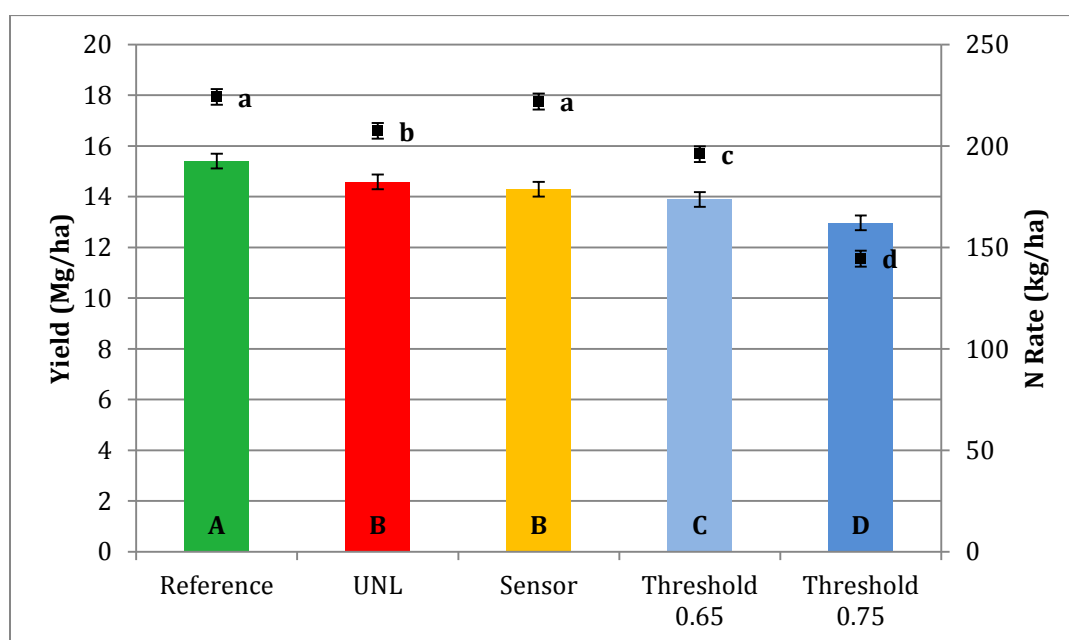


Figure 6: Whole strip treatment values for 09BR by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The sensor-based treatment yielded similarly to the UNL treatment, but received significantly more N. Each threshold treatment received significantly less nitrogen and yielded significantly less than the other treatments. This contrasts with Site

09HU (Figure 7) where threshold treatments yielded significantly higher than the sensor treatment while receiving significantly less N.

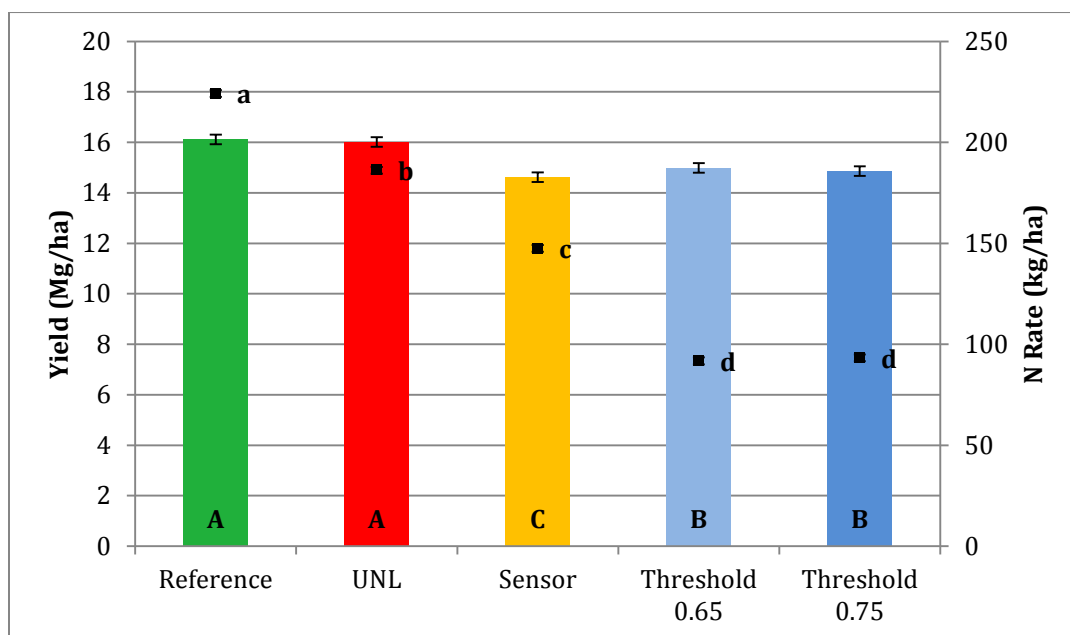


Figure 7: Whole strip treatment values for 09HU by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

At Site 09RA (Figure 8), grain yield for the UNL was significantly higher than the sensor treatment, but received a similar amount of N.

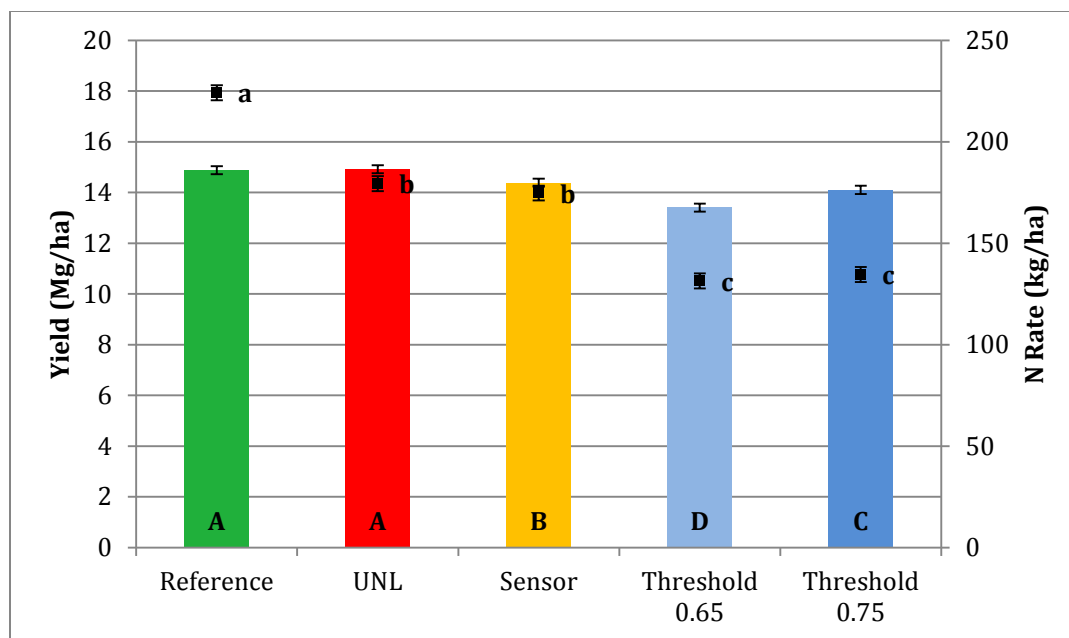


Figure 8: Whole strip treatment values for 09RA by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The T65 treatment yielded significantly less than all treatments, but received a similar amount of N as T75.

Combined Imposed Threshold Location-Grain Yield

To examine impacts of threshold implementation in detail where crop conditions were less ideal, we extracted data occurrences only in the direct area where the threshold treatments were imposed. Treatment values for UNL, reference, and sensor treatments were extracted, as described in the methods section. These “combined imposed threshold location values”, referring to areas where either threshold was imposed, attempt to reduce spatial variability by focusing the scope of analysis, which should provide an accurate measurement of threshold treatments in areas where they were intended.

This approach resulted in different responses for Site 09BR from the whole strip means, particularly the sensor treatment. In Figure 9 grain yields for all treatments tended to follow the same trend as the field length strips, but the total N applied in the sensor treatment was significantly higher than any of the other treatments, while yielding less than the reference treatment and similar to UNL.

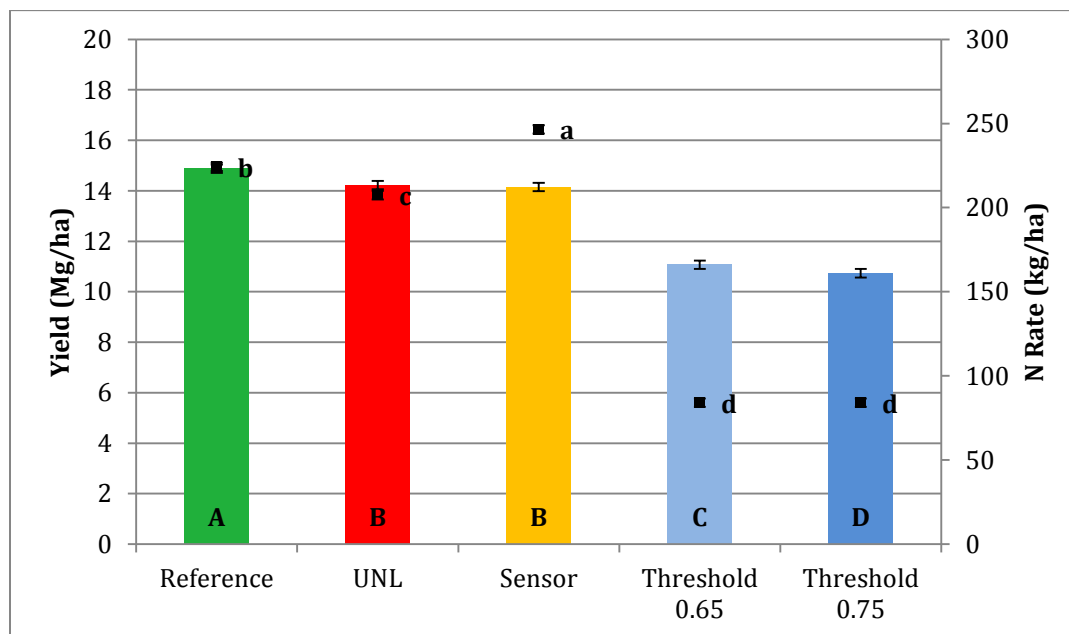


Figure 9: Combined imposed threshold values for 09BR by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The threshold treatments yielded significantly lower than other treatments and received significantly less N as well. Combined threshold imposed locations grain yield response at Site 09HU (Figure 10) was similar to that of the field length strip data.

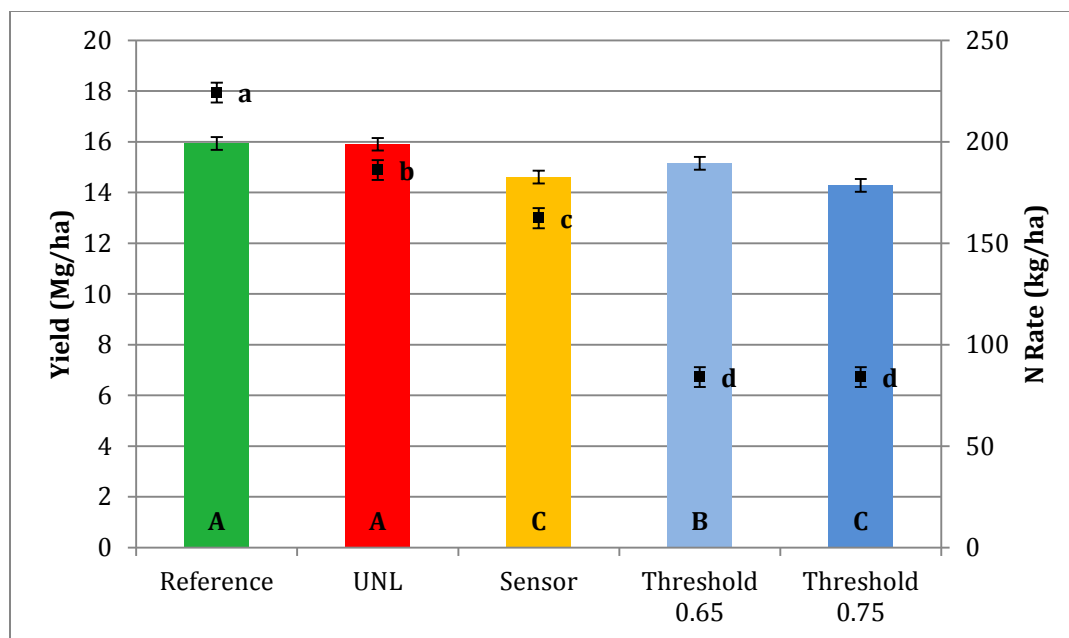


Figure 10: Combined imposed threshold values for 09HU by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

Grain yield for UNL was significantly higher than all treatments except the reference, which it was similar to. The sensor treatment yielded less than T65, but similar to that of T75. The N rate applied to the sensor treatment was significantly higher than either threshold, but less than the UNL treatment. Combined threshold location SI values for Site 09HU (Figure 11) show the sensor treatment SI values were significantly higher than either threshold treatment value.

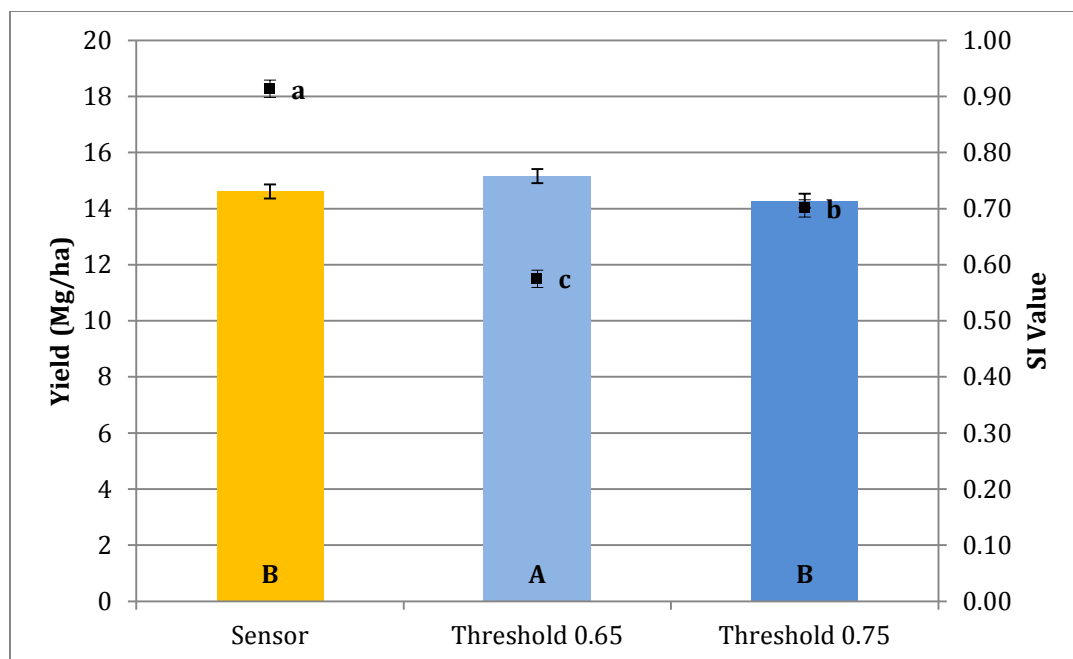


Figure 11: Combined imposed threshold values for 09HU by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

Threshold 0.75 had a significantly higher SI value than T65, but yielded significantly less, which was unexpected.

At Site 09RA, combined threshold location grain yield responded differently than the field length strip means. The reference, UNL, and sensor treatments yielded similarly, but the sensor treatment received a significantly higher N rate than every treatment except the reference (Figure 12).

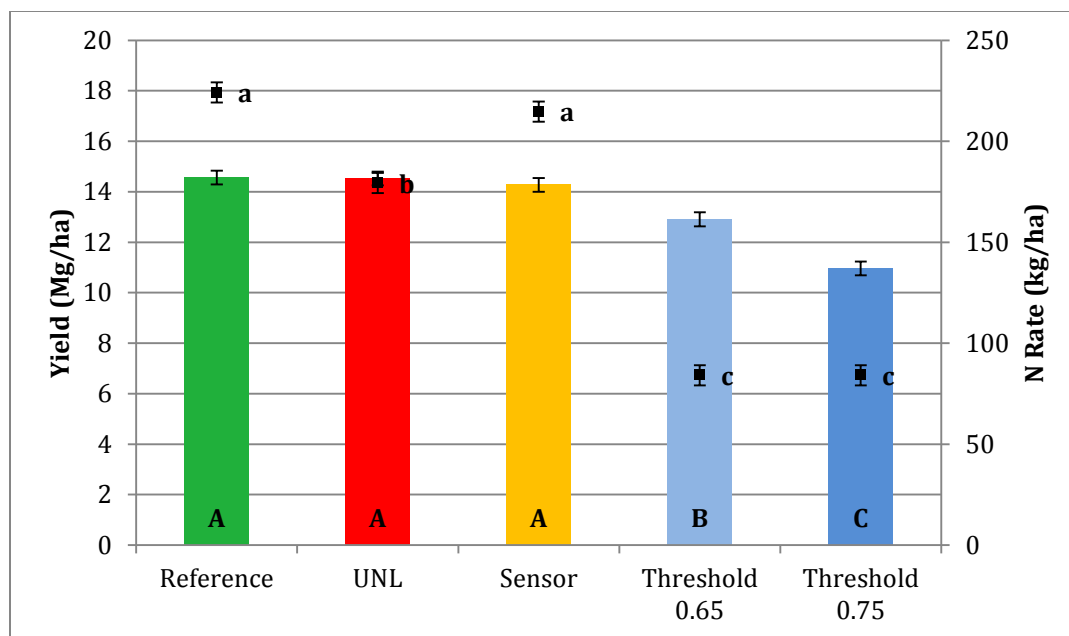


Figure 12: Combined imposed threshold values for 09RA by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The threshold treatments yielded less than other treatments and received less N. As was the case for Site 09HU, T75 yielded significantly lower than T65. Threshold 0.75 at the 09RA site had a similar SI value to T65.

Discussion

Field length strips grain yield responses to treatments for Site 09BR was as expected, the higher the N rate, the higher the grain yield. Threshold treatments yielded significantly lower than any of the other treatments, which suggests this method was ineffective for this site. However, for the combined threshold location values, we saw a different outcome. The sensor treatment received a significantly higher N rate than any other treatment while grain yield was not significantly higher

as a result. The combined threshold location SI value for the sensor treatment was 0.77 (Figure 13).

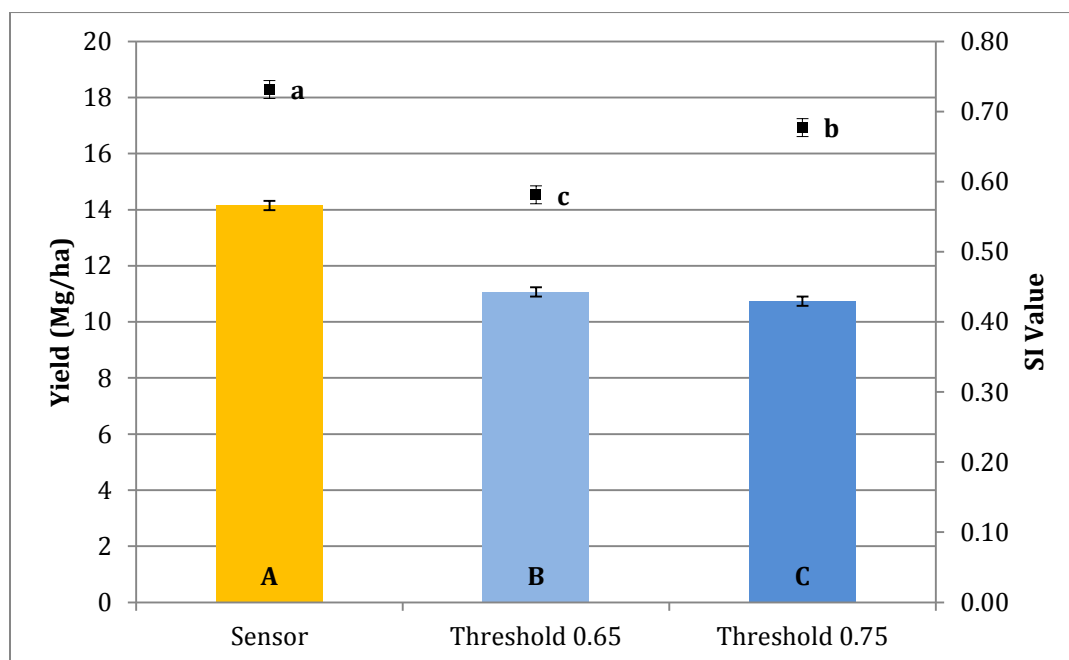


Figure 13: Combined imposed threshold values for 09BR by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

This is a fairly low SI value, approaching the first threshold of 0.75. The low SI value resulted in a higher average N rate, but there was not the same response in grain yield as the UNL treatment. This is likely because the UNL treatment received more N earlier in the growing season. Inadequate N supply early in the season for all sensor-based treatments may have resulted in unrecoverable N stress relative to the UNL treatment at this site. This site's low soil organic matter, 1.20%, (Table 3) and coarse textured soil (Table 2) make early season fertilizer N supply more critical to protecting yield potential.

Site 09HU provided unexpected results. The whole strip grain yield for the sensor treatment was significantly lower than threshold treatments, but received a significantly higher N rate. Figure 14 shows data from the neighboring small plot study in which there was a response of grain yield to N rate, but that there was also a large variance about this response.

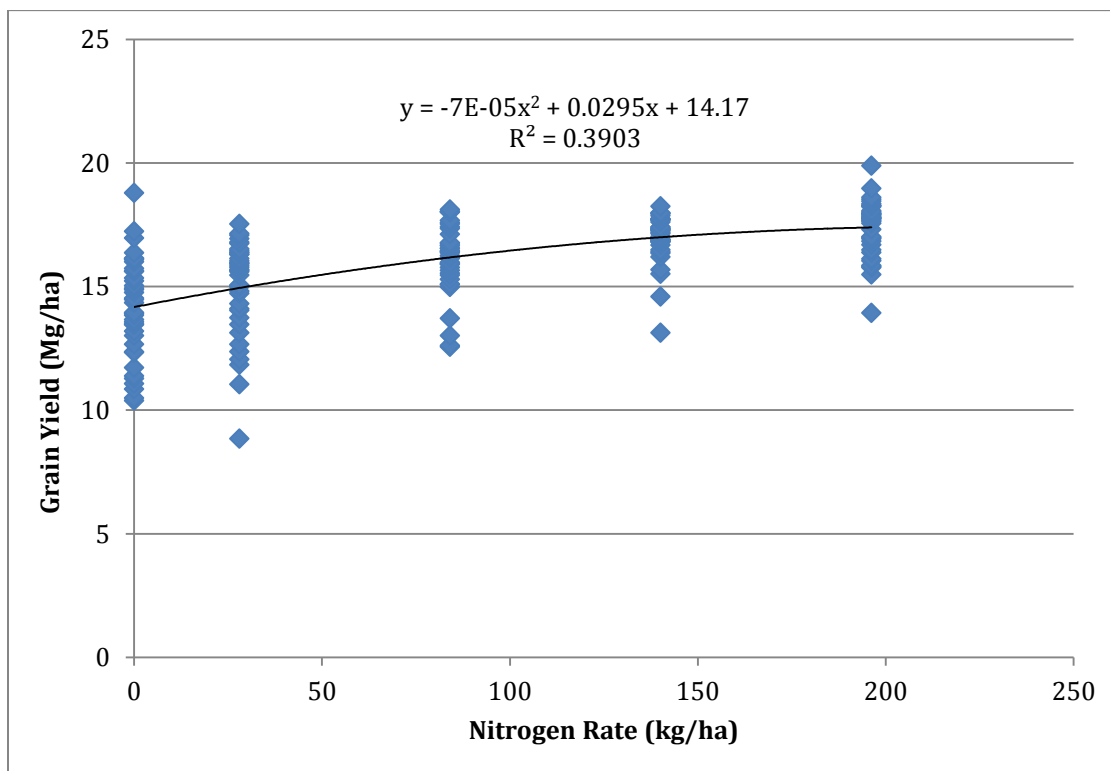


Figure 14: Grain yield response vs nitrogen rate, for Site 09HU.

Also, SI values for the sensor treatment in either the field length strips (Figure 15) or combined imposed threshold location (Figure 11), are significantly higher than the threshold treatments.

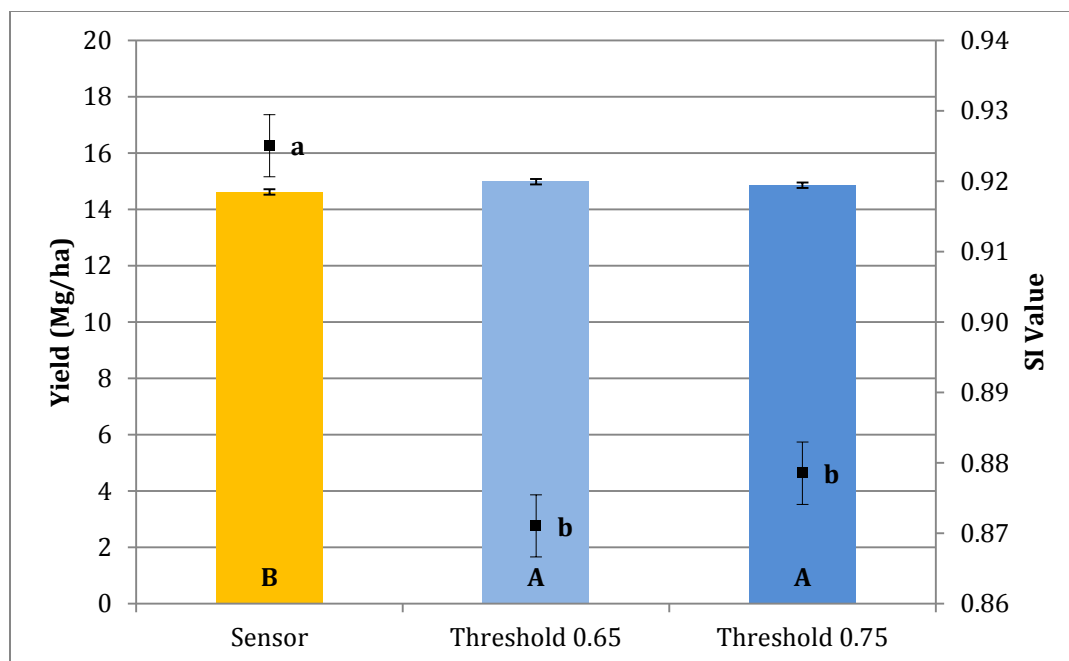


Figure 15: Whole strip treatment values for 09HU by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The higher SI values resulted in lower in-season N rates. This suggests that the crop was adequately supplied with N at the time of sensing, but later in the season N supply may have been inadequate. Most likely this resulted from or lower mineralization rates than assumed in the algorithm.

Site 09RA results showed a typical response of grain yield to N for field length strip values (Figure 8). However, the combined grain yield response (Figure 12) showed that the additional amount of N applied to the sensor treatment that was over the UNL treatment's N rate was not required to achieve similar grain yields. This is evidence that the algorithm may need to be adjusted to account for a soil that is providing more N later in the growing season from a larger mineralization potential.

2010 Grain Yield Response

Field Length Strips-Grain Yield

The 2010 treatments included a third threshold, with a SI cutoff value of 0.55 (T55). However, the only site of three evaluated with SI values low enough to impose this threshold was Site 10BR. At Site 10BR the whole strip grain yield values were not characteristic of typical grain yield response to N. The sensor treatment grain yield was similar to the UNL, T55, and T65 treatments (Figure 16).

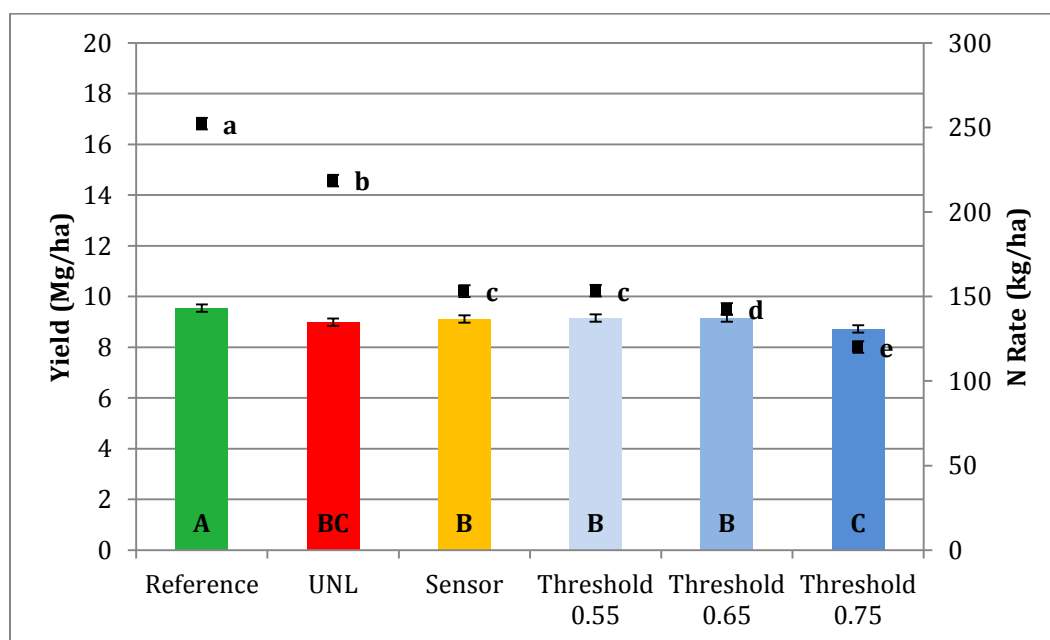


Figure 16: Whole strip treatment values for 10BR by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The N rate for the sensor treatment was similar to T55 and significantly higher than the other threshold treatments, but significantly less than the reference or UNL treatments. The T75 treatment yielded similarly to the UNL treatment and

significantly less than all other treatments, while receiving the least amount of N. Site 10HU had a typical response of grain yield to N (Figure 17).

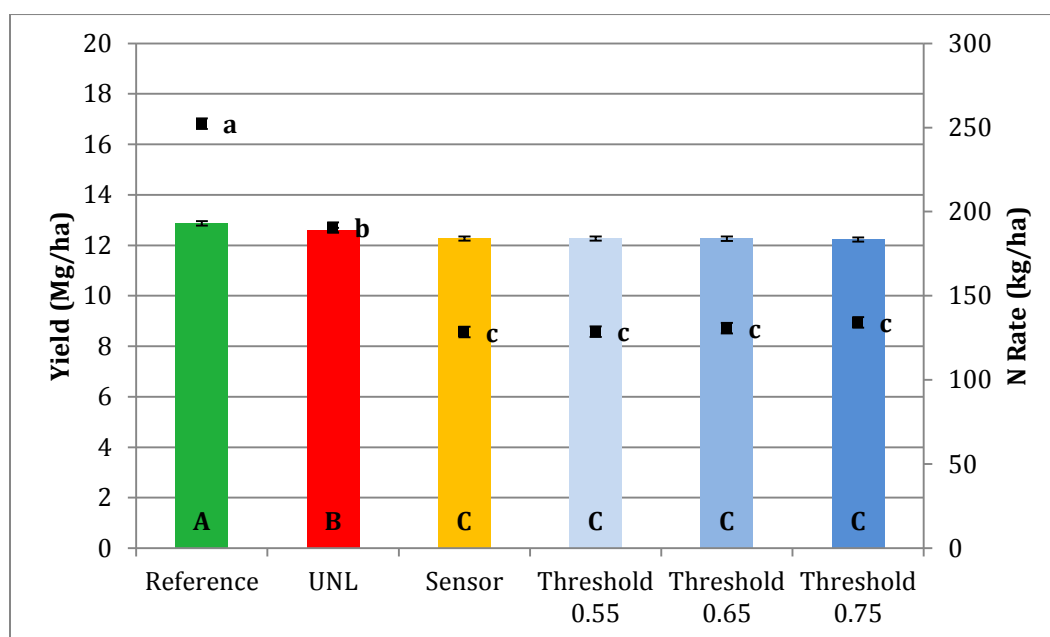


Figure 17: Whole strip treatment values for 10HU by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The reference treatment's grain yield was significantly higher than all other treatments and received the most N followed by a lower grain yield and N rate for the UNL treatment. The sensor treatment and all threshold treatments yielded similarly and received similar amounts of N; all less than the UNL treatment. The field length strip grain yield and N for Site 10LE are shown in Figure 18.

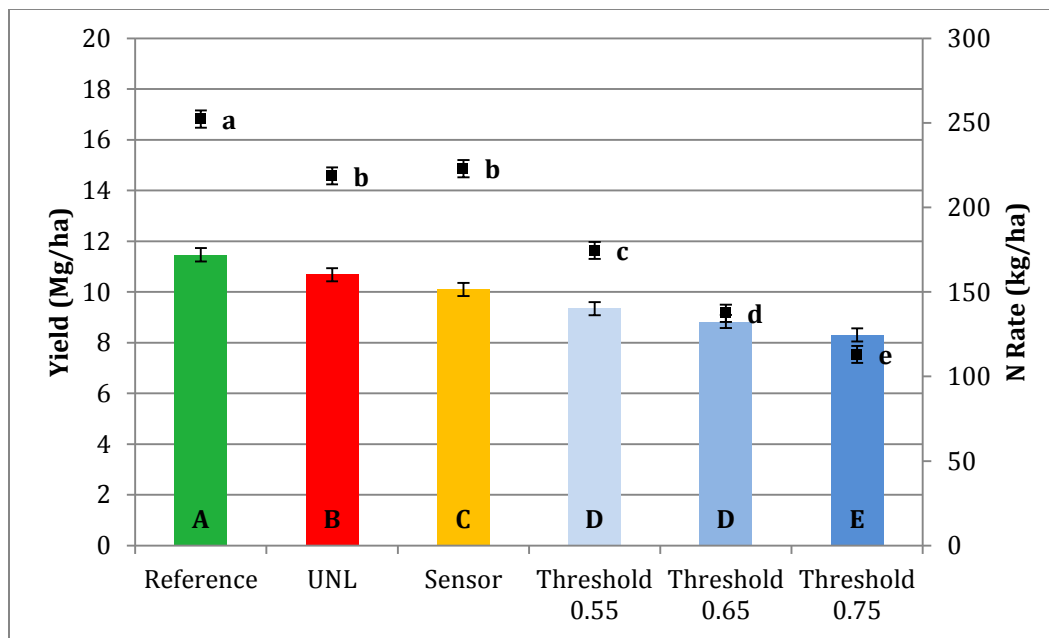


Figure 18: Whole strip treatment values for 10LE by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

There was a typical response of grain yield to N applied at this site. The reference treatment grain yield and N rate were significantly higher than all other treatments. The UNL treatment yielded significantly lower than the reference treatment, but significantly higher than the sensor treatment while receiving a similar amount of N as the sensor treatment. The threshold treatments yielded significantly less than each other with correspondingly lower rates of N.

Combined Imposed Threshold Location-Grain Yield

Figure 19 shows the combined threshold location grain yield values for Site 10BR.

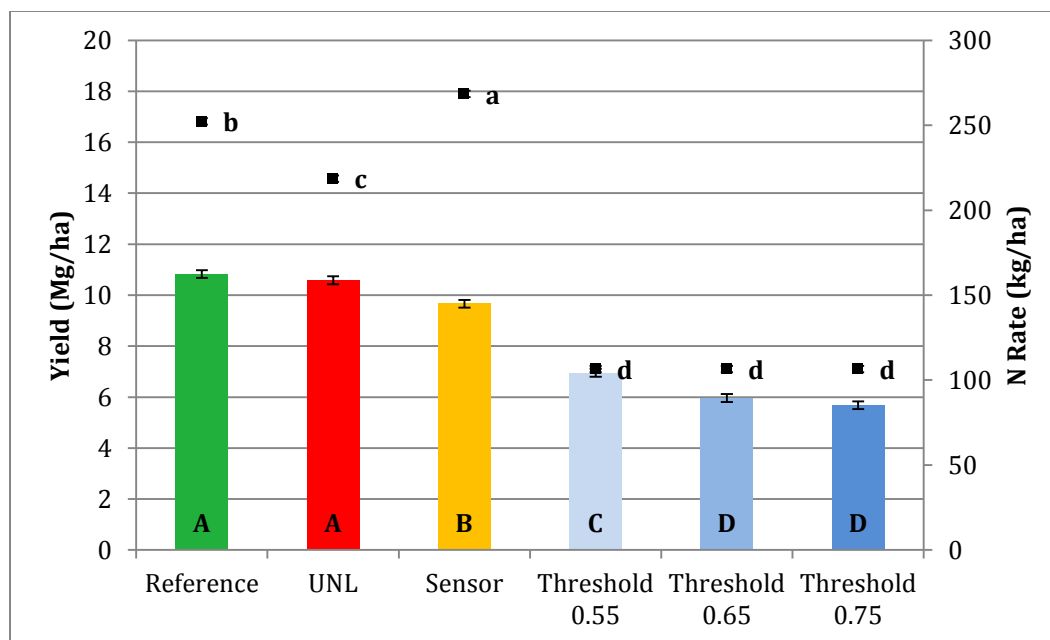


Figure 19: Combined imposed threshold values for 10BR by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The reference treatment yielded significantly higher than the UNL treatment while receiving more nitrogen. The sensor treatment received the highest amount of nitrogen compared to the other treatments, but yielded significantly less than the reference and UNL treatments. Threshold treatments T65 and T75 yielded similarly, but less than treatment T55. All threshold treatments received the same amount of N. The SI values for this site are shown in Figure 20.

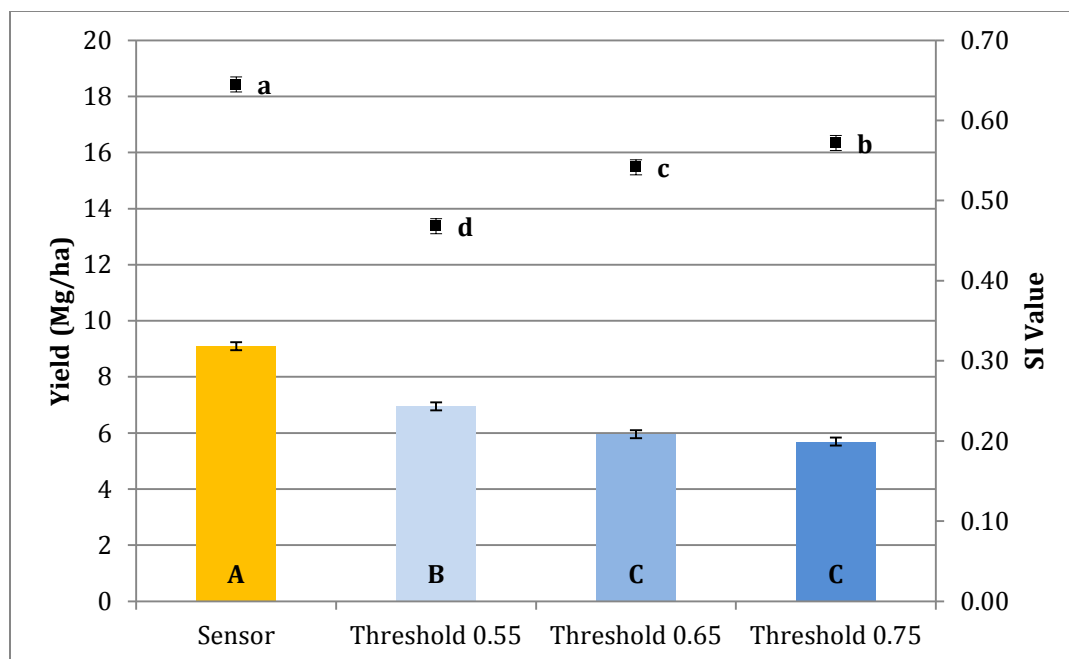


Figure 20: Combined imposed threshold values for 10BR by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The sensor treatment had a significantly higher SI value than all threshold treatments. Threshold 0.55 had a significantly lower SI value than either the T65 or T75 treatments.

Site 10HU also showed a different response for combined threshold location compared to the field length strip values. At this site, there was relatively little yield response to N (Figure 21).

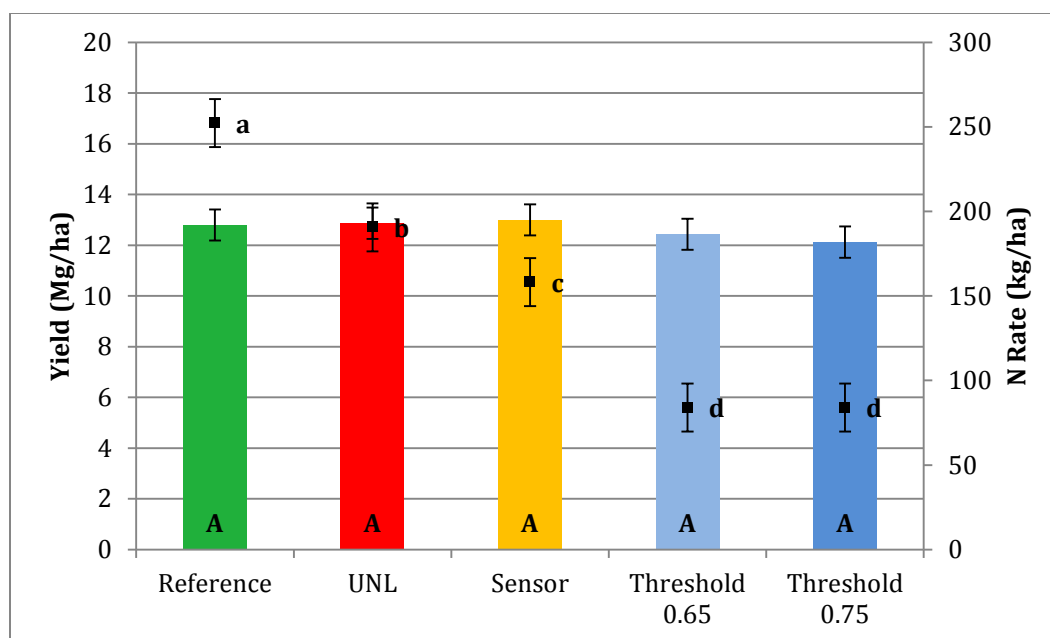


Figure 21: Combined imposed threshold values for 10HU by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

All treatments yielded similarly, but received significantly different amounts of nitrogen. The threshold treatments received the least amount of nitrogen. The associated grain yields for the threshold treatment tended to be lower than the other treatments, but not significantly. The combined threshold location SI values for Site 10HU show that the SI values are significantly different for each treatment, but yield is not different (Figure 22).

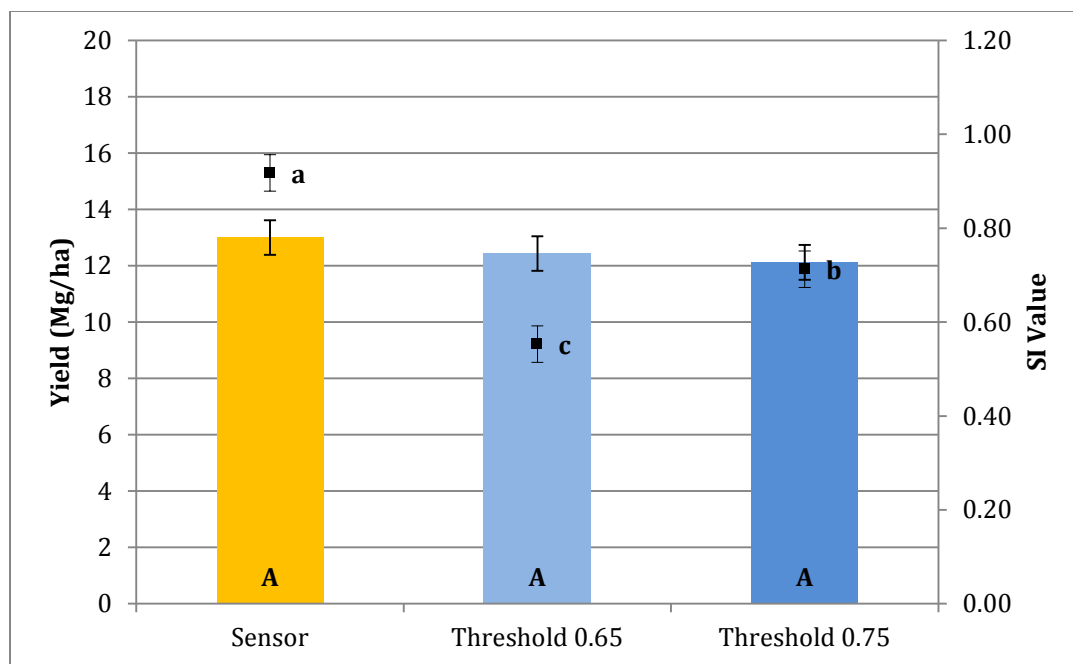


Figure 22: Combined imposed threshold values for 10HU by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

Site 10LE combined threshold location grain yield showed little to no response to N above a certain rate (Figure 23).

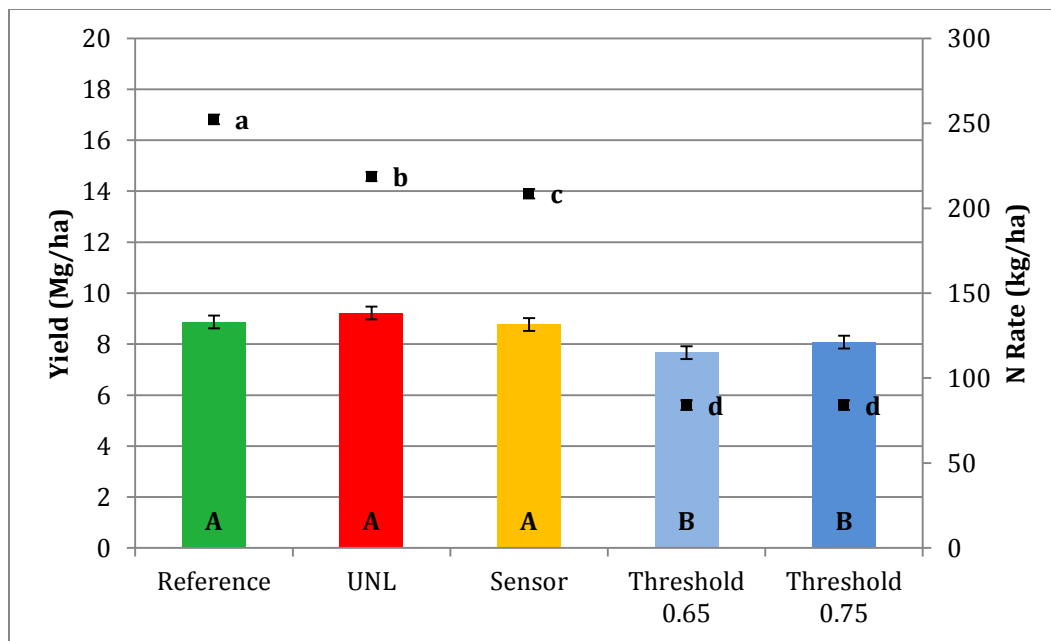


Figure 23: Combined imposed threshold values for 10LE by treatment for grain yield in bar format on the primary axis. Values by treatment for the total nitrogen received in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The reference, UNL, and sensor treatments yielded similarly while having significantly different N rates. The threshold treatment yield were significantly less than the other treatments, and received significantly less N as well.

Discussion

The 10BR site provided unexpected responses of grain yield to N (Figure 16). Although the UNL treatment yield was similar to the sensor treatment, the UNL treatment yield trended noticeably lower than the sensor treatment. At the same time the UNL treatment received significantly more N, which if the UNL treatment had a similar response to N as the reference treatment, there would have been a higher yield for the UNL treatment. This may be explained by the application timing for the UNL treatment versus the other treatments. The UNL treatment and

reference received all N at the beginning of the growing season. In 2010 there was ample rainfall (Figure 24) after the initial application of N.

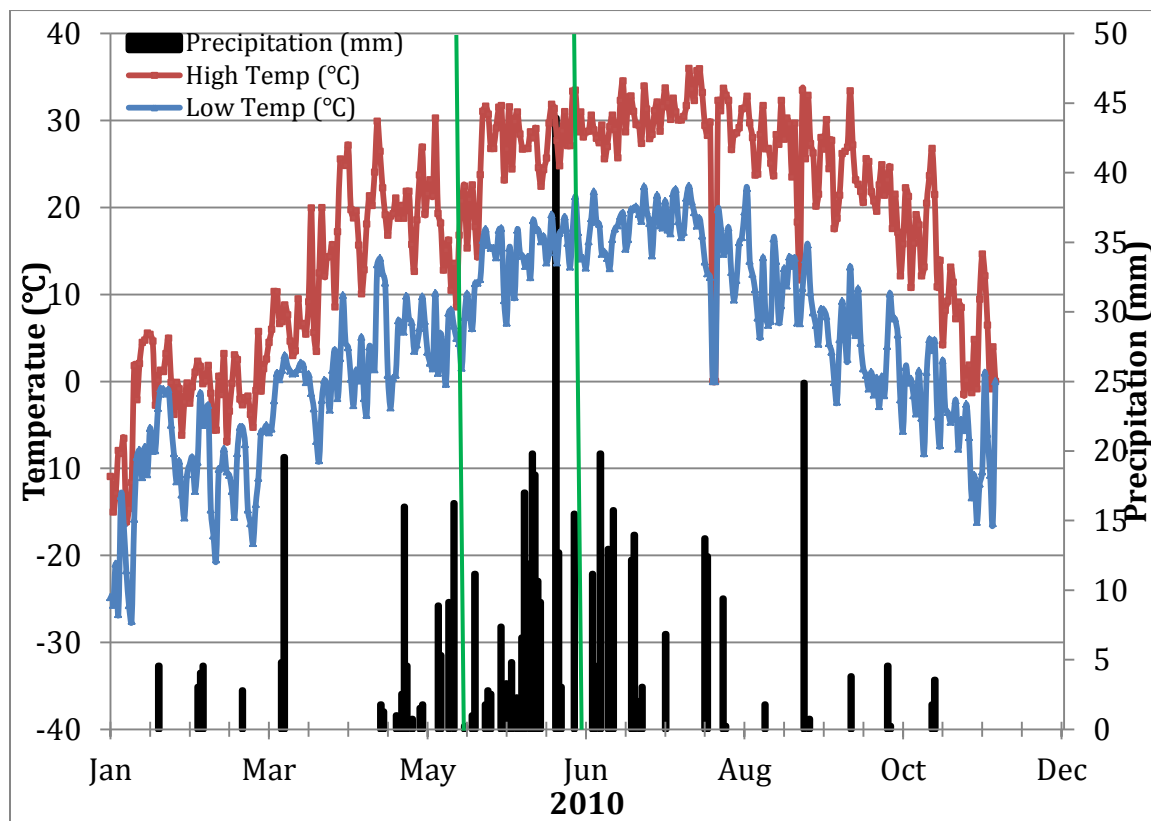


Figure 24: Site 10BR temperature and precipitation history for 2010. Green lines indicate date of N application.

This most likely caused nitrate to be lost via leaching in this coarse-textured soil. It is also worth noting that the sensor treatment yielded similarly to two of the threshold treatments, T55 and T65. This is concerning, as the quantity of points where the threshold was imposed was quite high (Figure 25).

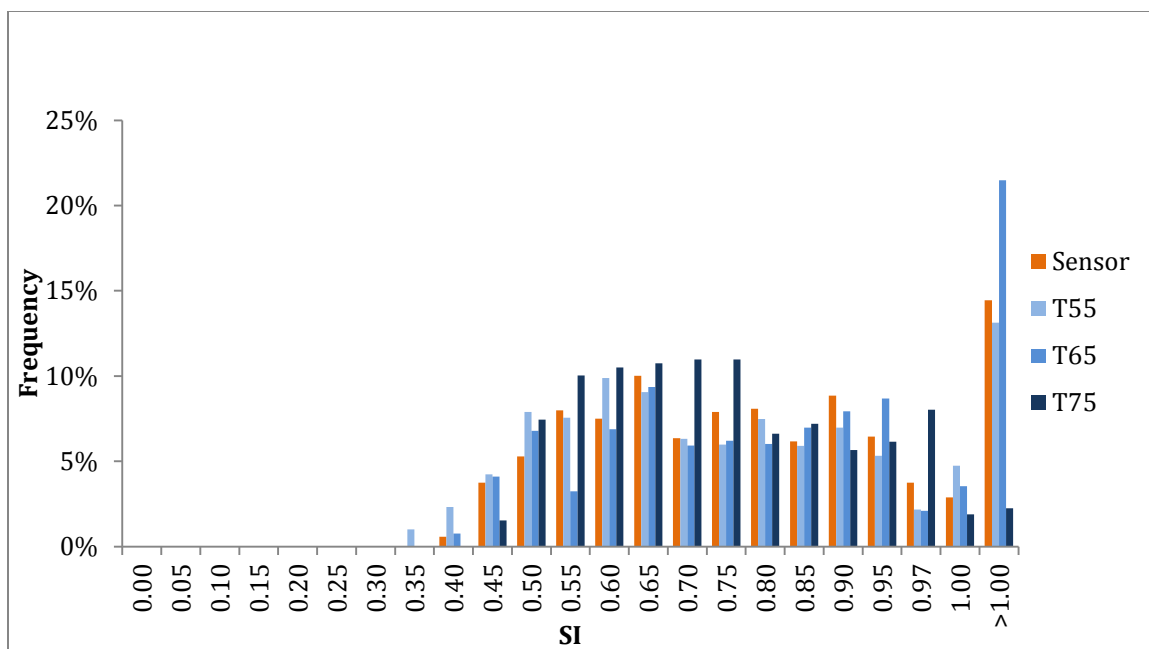


Figure 25: Distribution of SI values by treatment for 10BR

This is reflected in the lower nitrogen rates of the threshold treatments, but the sensor treatment did not have any points where nitrogen was restricted as a result of having too low of an SI value. The sensor treatment did have several points where the SI value was greater than 0.97, which is the upper cutoff to the algorithm. There were several points where the nitrogen rate was lower because of a higher SI value. As a result, these areas either became deficient later into the season from lack of additional nitrogen and/or the reference treatment strips were not representative at the time of application.

Site 10HU had a typical response of grain yield to N (Figure 17). The sensor treatment and threshold treatments all yielded similarly and received similar amounts of N. This is surprising as the reference strip, which guides these

treatments, yielded significantly higher. More than half of the application data points for the sensor treatment had SI values above 0.97 (Figure 26).

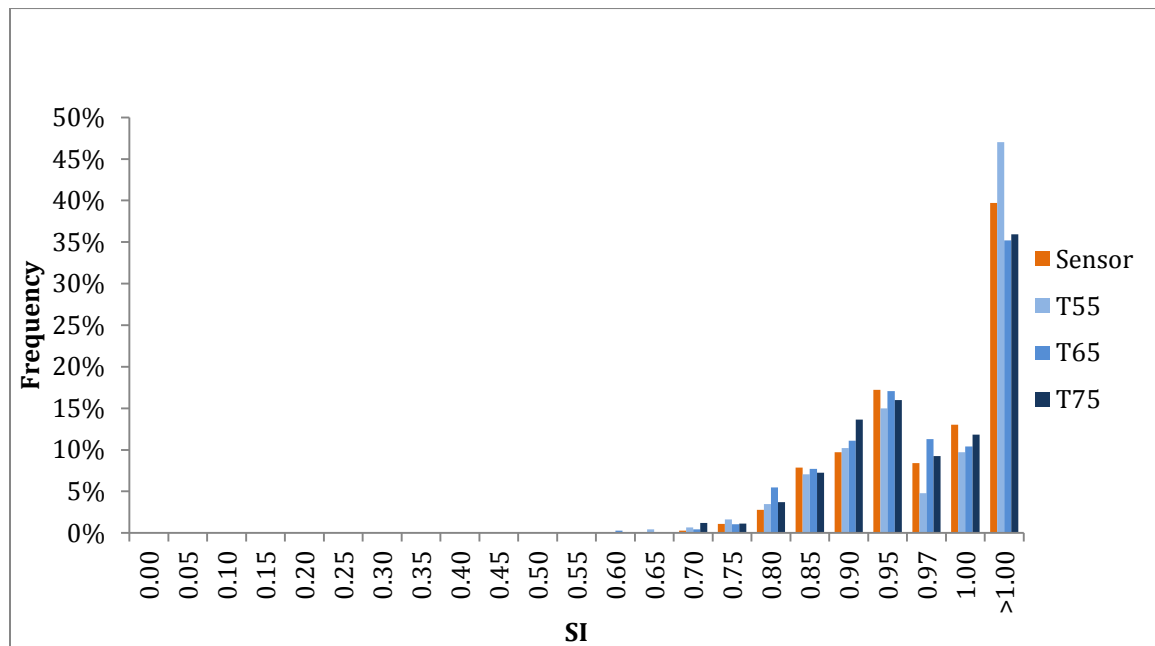


Figure 26: Distribution of SI values by treatment for 10HU

This supports that the reference strip was sufficient at the time of application, and that the reference treatment had sufficient nitrogen applied to supply the crop for the rest of the season. This suggests that the sensor and threshold treatments, however, did not. The 84 kg ha⁻¹ of nitrogen applied supplied this crop at least up to the sensing application, but the nitrogen supply must have run out somewhere beyond this time point, which caused a deficiency and ultimately a loss of yield as a result.

Economic and Productivity Analysis

2009 Growing Season

The field length strip economic analysis used \$0.24 kg⁻¹ for the grain price and \$1.32 kg⁻¹ for the N price. These prices reflect market prices during the time of this analysis. Profit was calculated using Equation 9.

Equation 9

$$Profit (\$) = (Yield * Grain Price) - (N rate * N Price)$$

The partial factor productivity (PFP) was calculated for all sites using Equation 10.

Equation 10

$$PFP = Yield (kg ha^{-1}) / N applied (kg ha^{-1})$$

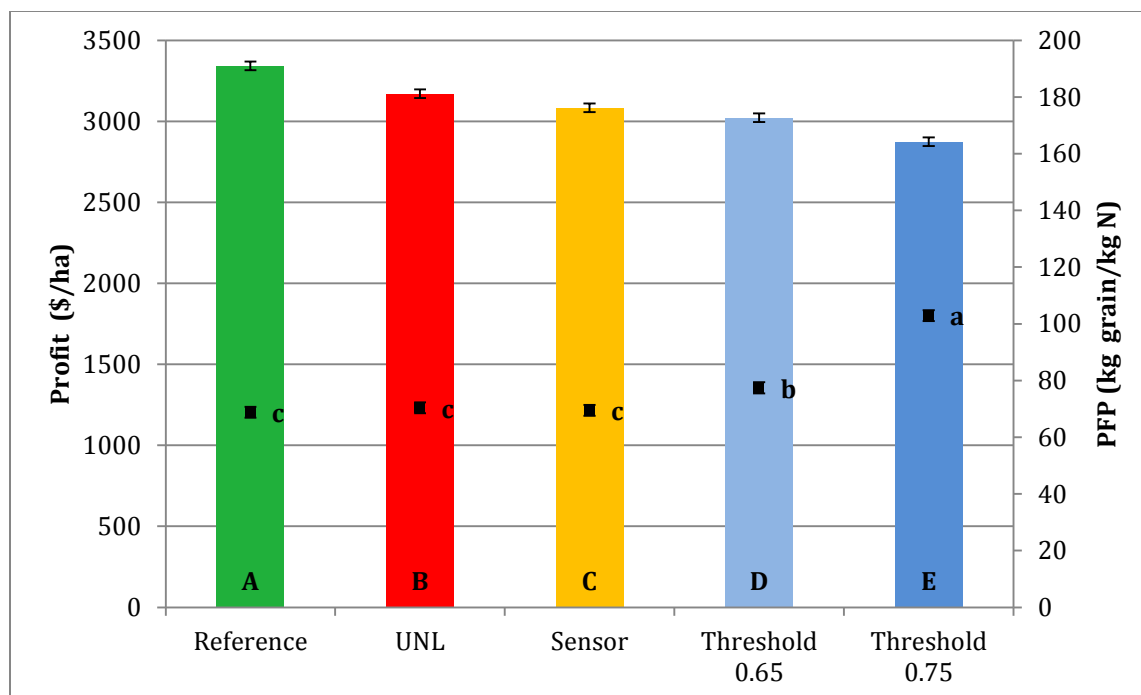


Figure 27: Whole strip treatment values for Site 09BR by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

Results for Site 09BR show the reference treatment being the most profitable followed by lower profit with the UNL, Sensor, T65, and T75 treatments respectively (Figure 27).

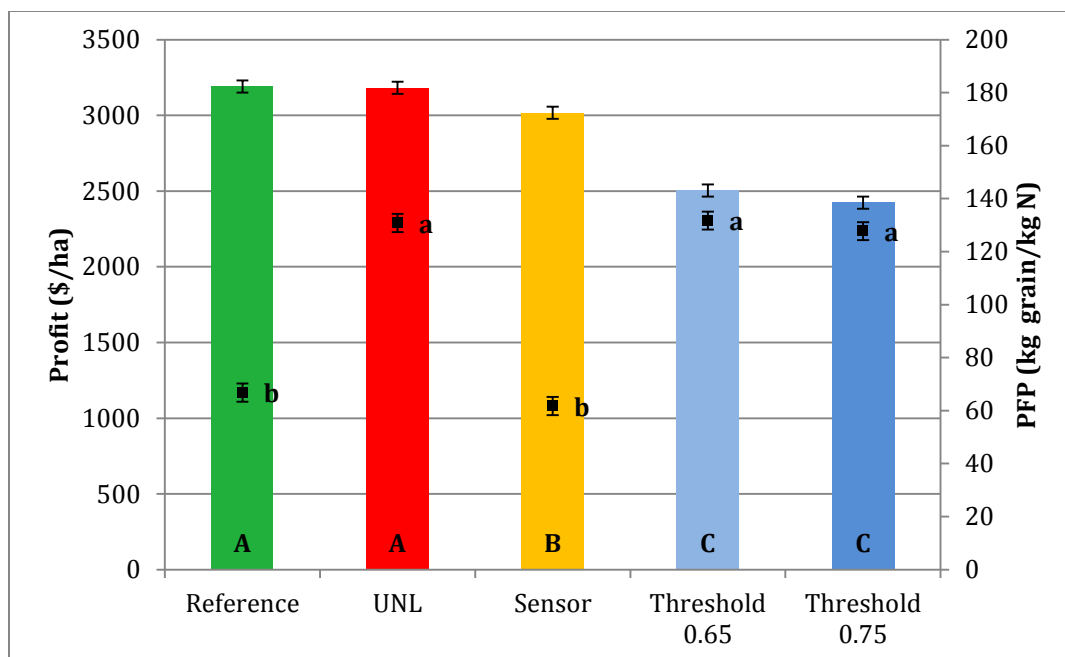


Figure 28: Combined imposed threshold values for Site 09BR by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The PFP for Site 09BR followed an opposite trend as profit with the highest PFP being T75. The combined imposed threshold profit and PFP for Site 09BR had a different outcome from that of the whole strips (Figure 28). The most profitable treatments were the Reference and UNL treatments, but the UNL treatment had a significantly higher PFP than the Reference treatment, similar to both threshold treatments. The profit for the sensor treatment was lower than the UNL treatment, but higher than both threshold treatments; however, the PFP was lowest for the sensor treatment along with the reference treatment.

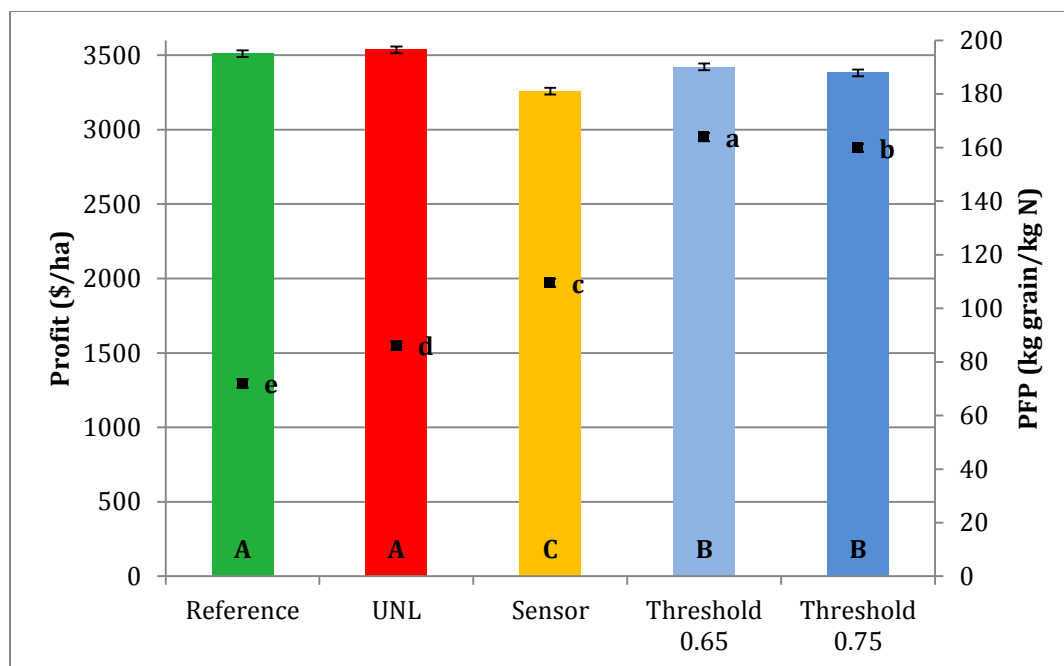


Figure 29: Whole strip treatment values for Site 09HU by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

For Site 09HU the sensor treatment was the least profitable (Figure 29). Both threshold treatments had similar profits, but T65 had a higher PFP. The most profitable treatments were both the Reference and UNL treatments.

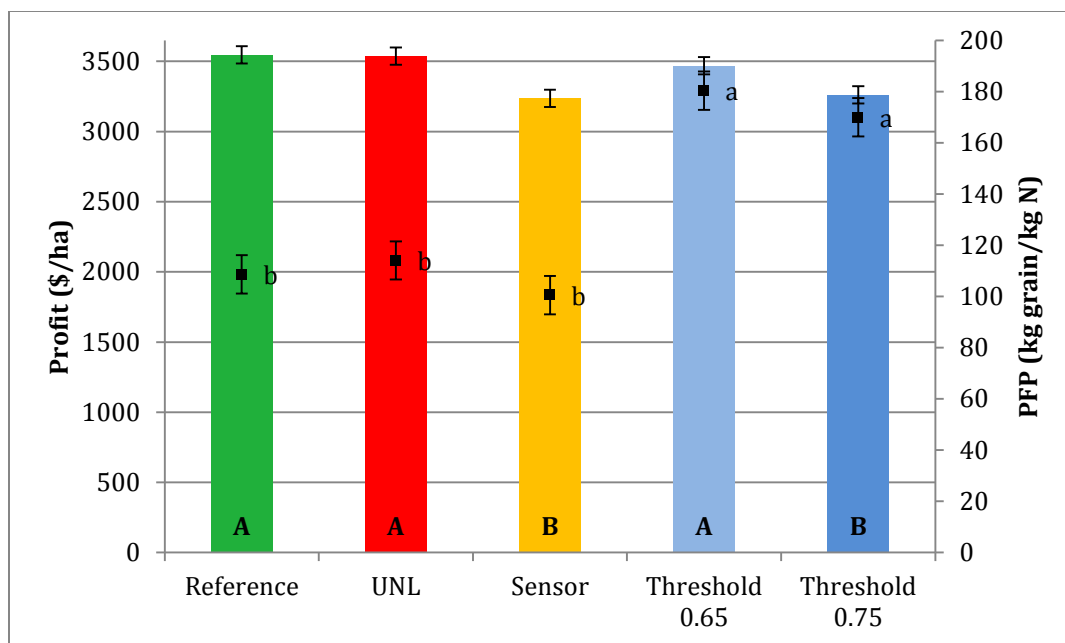


Figure 30: Combined imposed threshold values for Site 09HU by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The combined imposed threshold location profits for Site 09HU can be seen in Figure 30. The Reference, UNL and T65 treatments had the highest profit, and the sensor and T75 treatments were the least profitable.

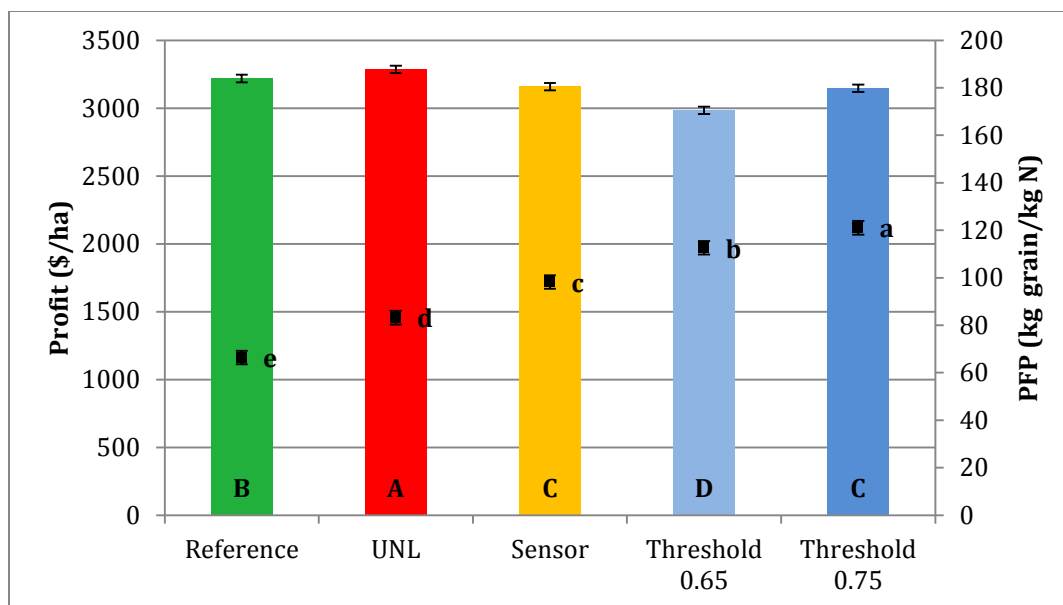


Figure 31: Whole strip treatment values for Site 09RA by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

At site 09RA (Figure 31) the UNL treatment was the most profitable followed by the Reference, sensor, T75, and T65 treatments respectively.

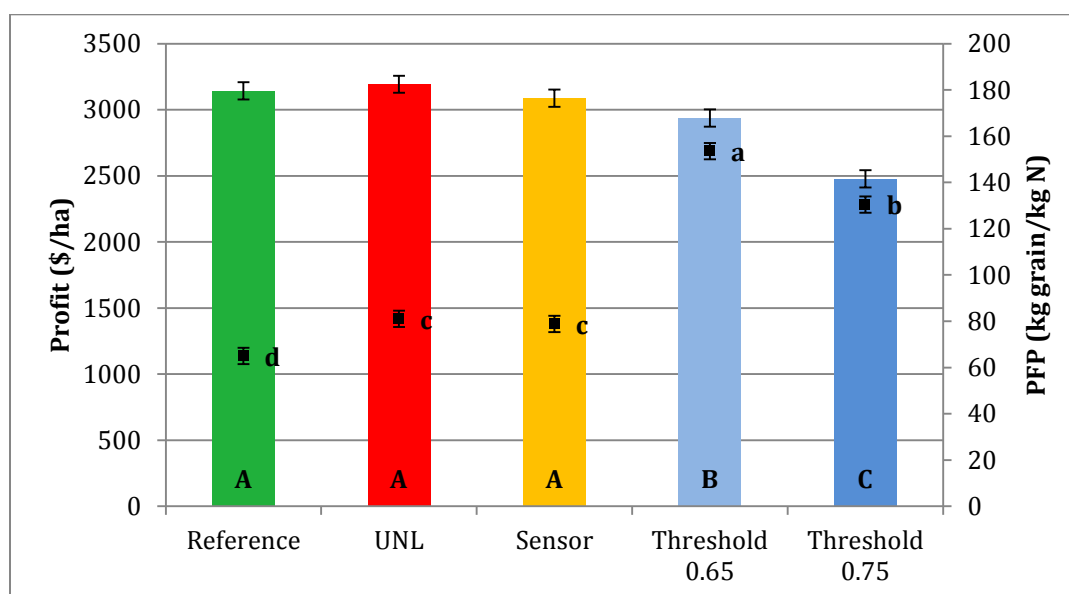


Figure 32: Combined imposed threshold values for Site 09RA by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The combined imposed threshold location results (Figure 32) show that the Reference, UNL, and sensor treatments had the highest profitability, but a lower PFP than the less profitable threshold treatments.

2010 Growing Season

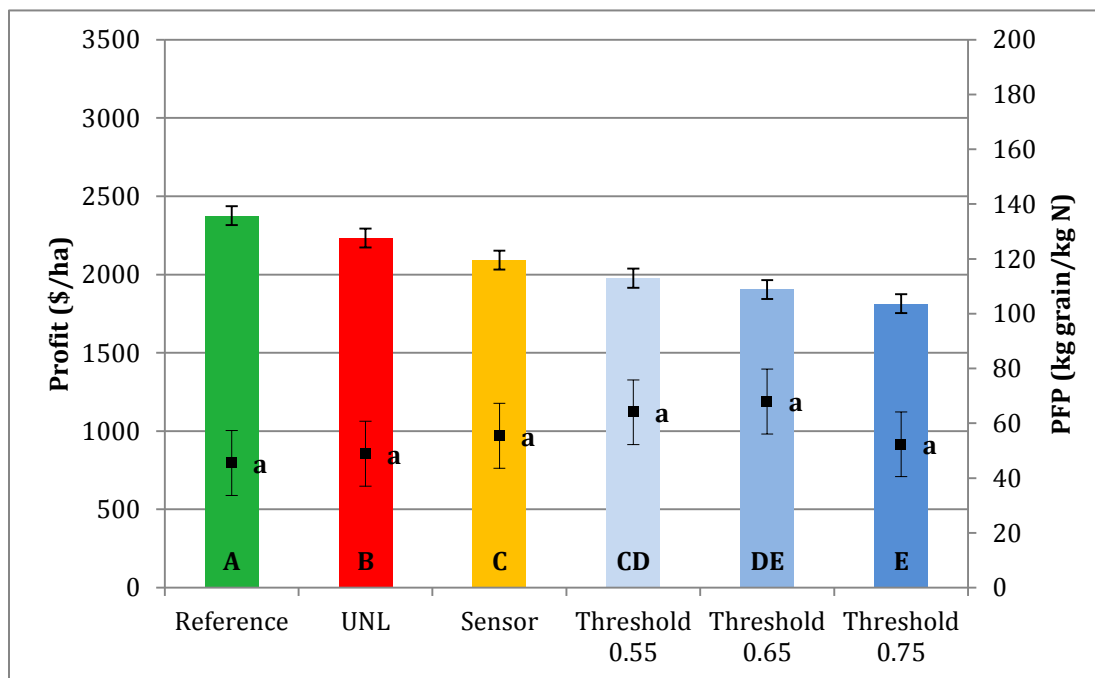


Figure 33: Whole strip treatment values for Site 10BR by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The profit comparisons for Site 10BR field length strips are shown in Figure 33. The Reference treatment was the most profitable followed by the UNL treatment. The sensor treatment was less profitable than the UNL treatment, but similar to T55. Threshold 0.65 and T75 were similar in profit to each other. The PFP values were similar for all treatments.

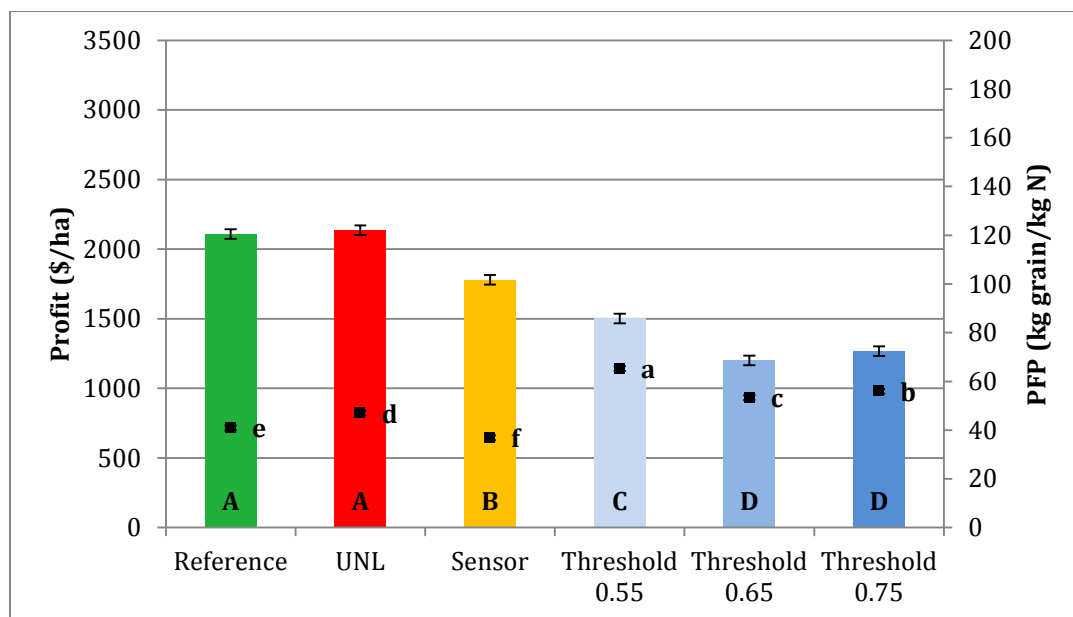


Figure 34: Combined imposed threshold values for Site 10BR by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The combined threshold location profit comparisons are shown in Figure 34. The Reference and UNL treatments were the most profitable. The sensor treatment was less profitable than the UNL treatment, but higher than all threshold treatments. Threshold 0.55 was the most profitable threshold treatment, and had the highest PFP among all treatments. The sensor treatment had the lowest PFP.

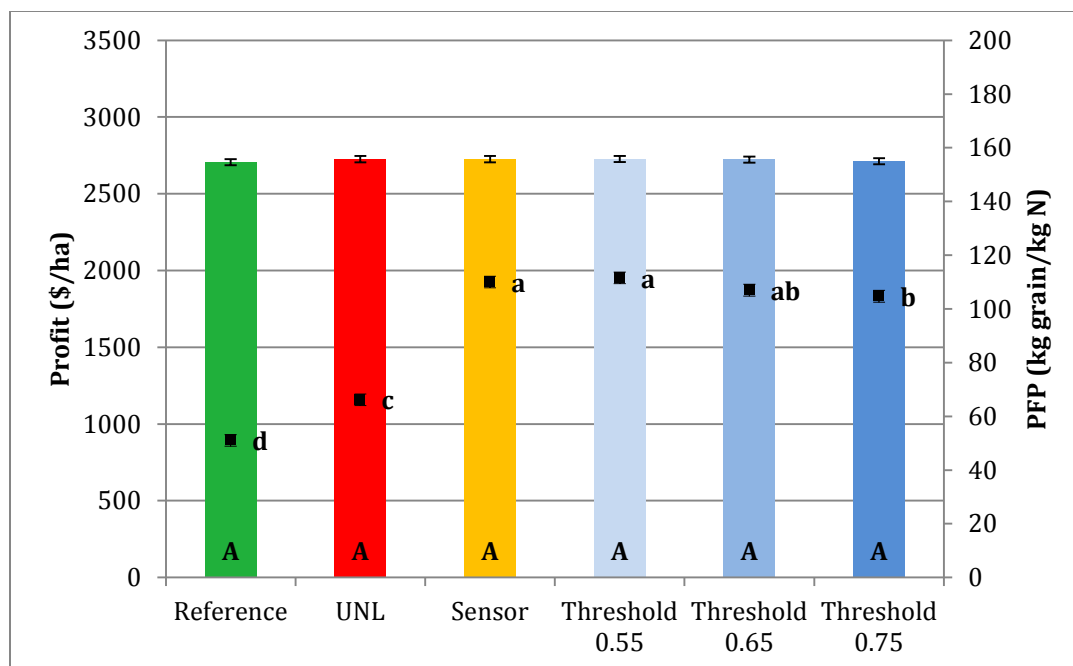


Figure 35: Whole strip treatment values for Site 10HU by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

All treatments at Site 10HU were similar in terms of profit for the field length strips (Figure 35). The highest PFP for this site was the sensor, T55, and T65 treatments, and the lowest PFP was the Reference treatment.

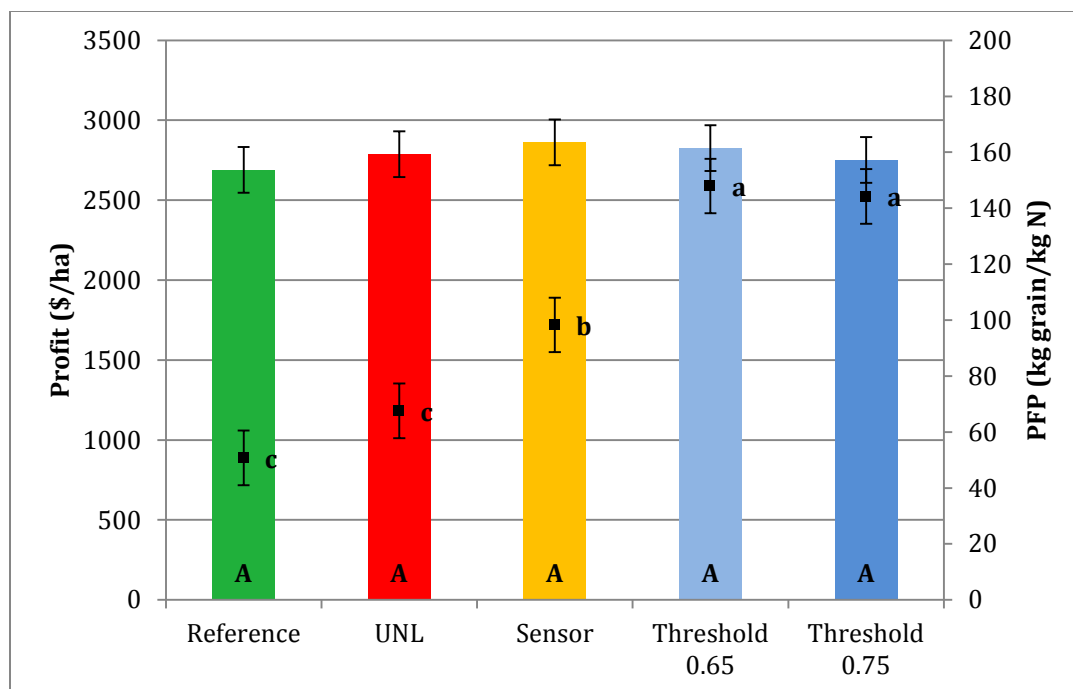


Figure 36: Combined imposed threshold values for Site 10HU by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

The profit results for the combined threshold locations (Figure 36) show that all treatments are similar. The partial factor productivity is different among treatments, with the threshold treatments having the highest PFP and the Reference and UNL treatments having the lowest.

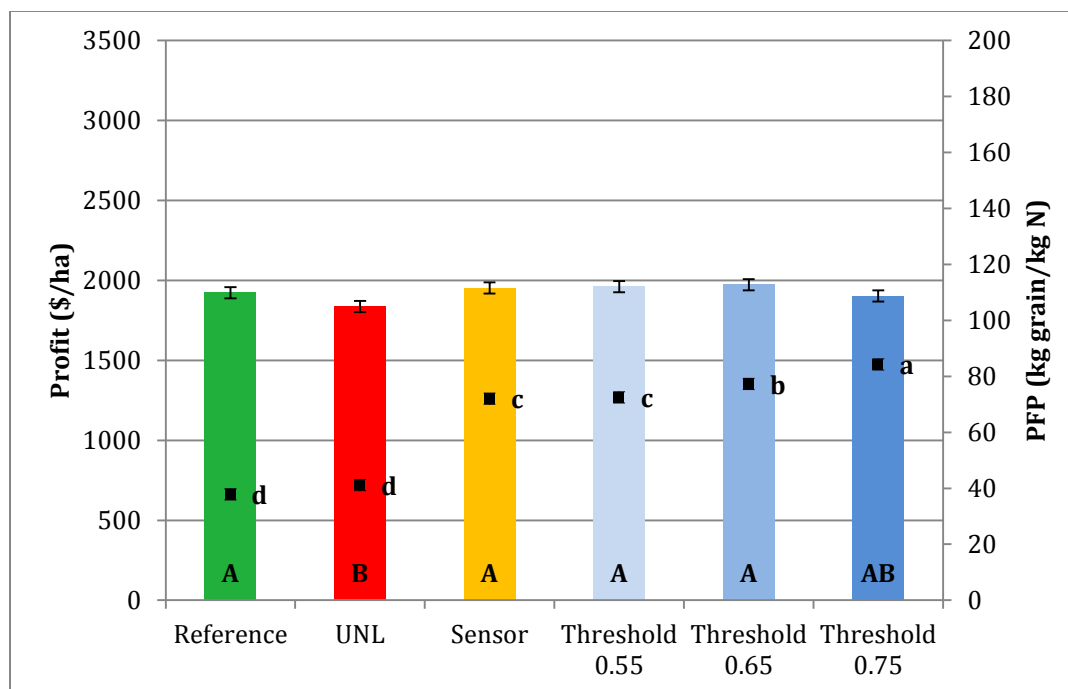


Figure 37: Whole strip treatment values for Site 10LE by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

Site 10LE profit results for the field length strips are shown in Figure 37. The reference, sensor, T55, T65, and T75 treatments were the most profitable and similar. The UNL treatment was the least profitable. The PFP was highest for T75, and the lowest PFP was the Reference and UNL treatments.

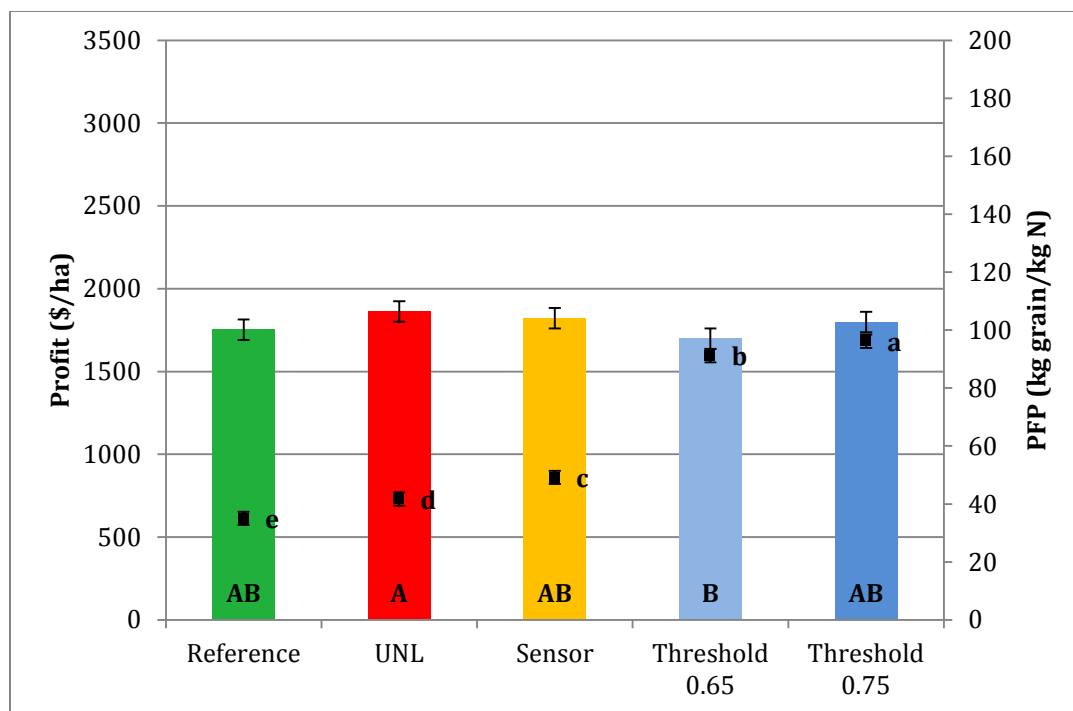


Figure 38: Combined imposed threshold values for Site 10LE by treatment for profit taking only N rate into account in bar format on the primary axis. Values by treatment for the PFP in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

This trend was different for the combined imposed thresholds (Figure 38). The most profitable treatments were the UNL, sensor, and T75 treatments, and the least was T65. The highest PFP was T75, and the lowest PFP was the Reference treatment.

Discussion

There was no clear trend for the sites with regards to profitability. The UNL treatment was the most profitable for most sites, but not in all cases. The PFP was widely ranging. The sensor-based treatments, either with or without thresholds imposed, always had the highest partial factor productivity of any of the treatments, unless there were no differences in PFP across all treatments. Most often PFP was

highest with one or more of the threshold treatments, but generally this was associated with lower profit.

Conclusion

Evaluation of SI thresholds was confounded by the unexpected response of the sensor treatment. Since the threshold treatments were based on the sensor treatment, we wanted to be able to compare the threshold treatment response with the response of the sensor treatment. In many cases the uniform application for either the UNL or reference treatments yielded better than the sensor based treatments (sensor and thresholds). If we were only comparing the effectiveness of the threshold treatments, we have found that the thresholds were largely ineffective. The threshold treatments made up a large percentage of the applied area at some sites such as 10BR (Figure 25), but a small percentage at sites such as 10HU (Figure 26). We found this is not the result of a similarly deficient corn plants, but an artifact of the application method. In the more coarse-textured (Table 2) Sites 09BR and 10BR, the response of the sensor based treatments was affected by a more deficient plant at sensing time. The initial application of N to the treatments did not provide enough N supply to prevent an irrecoverable deficiency, or that the deficiency was so great that the amount of N required to compensate for the deficiency was greater than had a uniform application been applied instead. The opposite conclusion can be drawn from the fine-textured (Table 2) Sites 09HU, 10HU, and 09RA. The initial application of N to the treatments provided a supply of N that extended at least until the point of sensing and application. This allowed for a higher SI value at the time of sensing, but the initial supply of N did not provide enough N for the rest of the season. As a result, the crop became deficient and yield

suffered. Analysis of the combined imposed threshold location was used to eliminate spatial variability, but the results suggest that there was significant variability at this scale. This was shown by comparing the SI values of the sensor based treatments for each site. If there was a lack of spatial variability, the SI values would be statistically similar, and this was not the case.

There was no clear economic benefit from using the sensor or sensor based threshold treatments. The uniform UNL treatment was the most profitable most of the time. The highest partial factor productivity was generally with one or both of the threshold treatments, but treatments with thresholds imposed were generally less profitable than other treatments. .

Further research is needed to refine the current approach to account for the site's soil mineralization potential as it occurs spatially. Different initial rates of N fertilizer are needed for different soil types, and more than one sensing application may be needed.

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Appendix

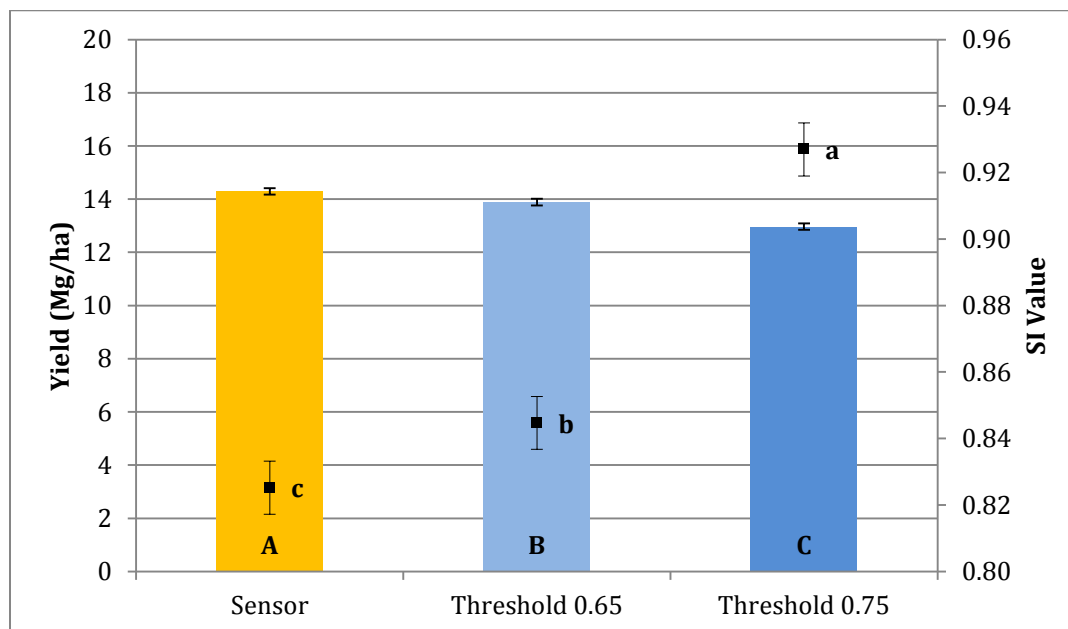


Figure A.1: Whole strip treatment values for 09BR by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different (p=0.05).

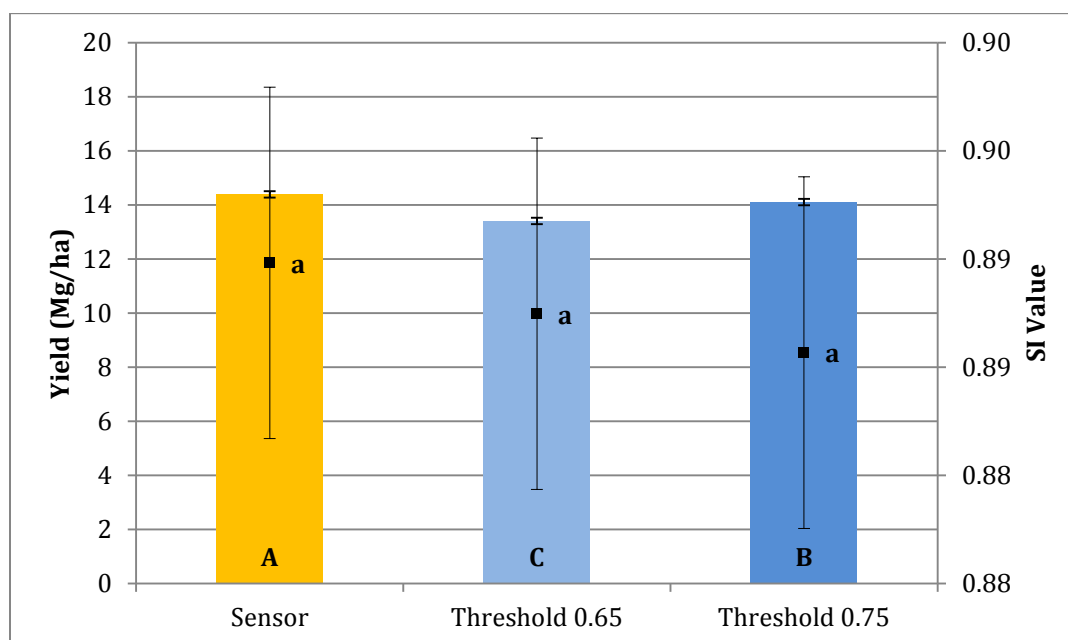


Figure A.2: Whole strip treatment values for 09RA by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different (p=0.05).

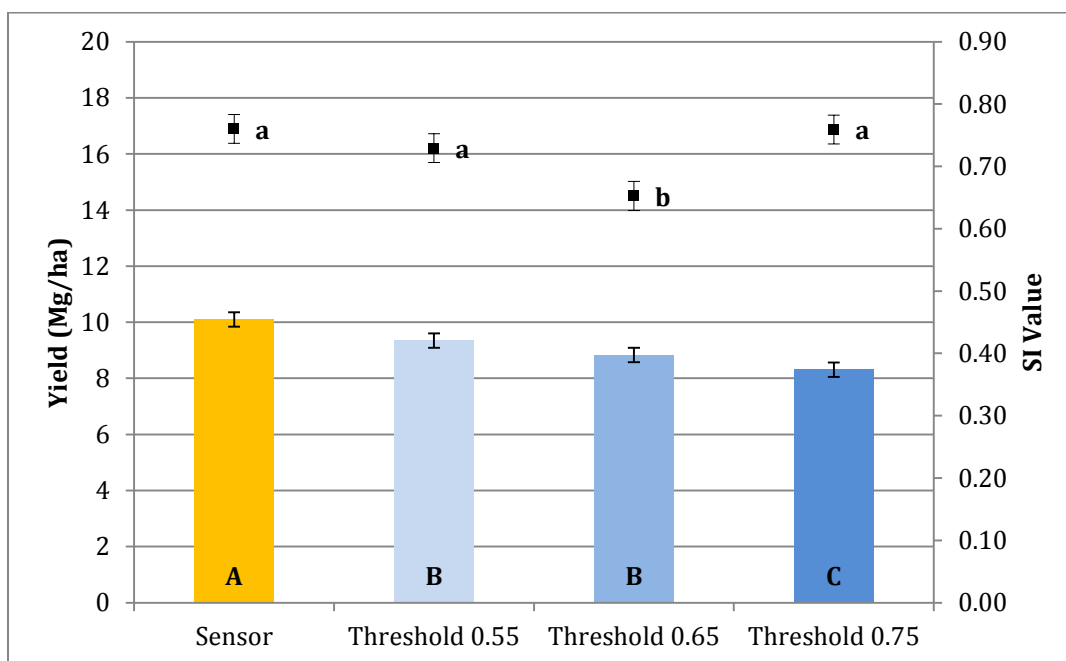


Figure A.3: Whole strip treatment values for 10BR by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

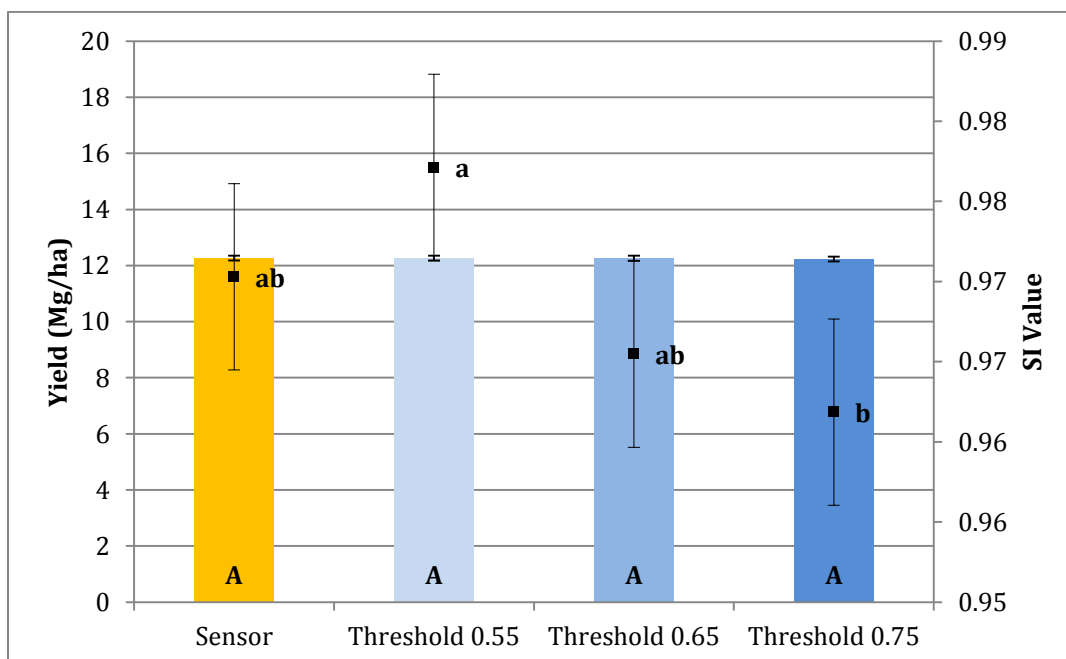


Figure A.4: Whole strip treatment values for 10HU by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

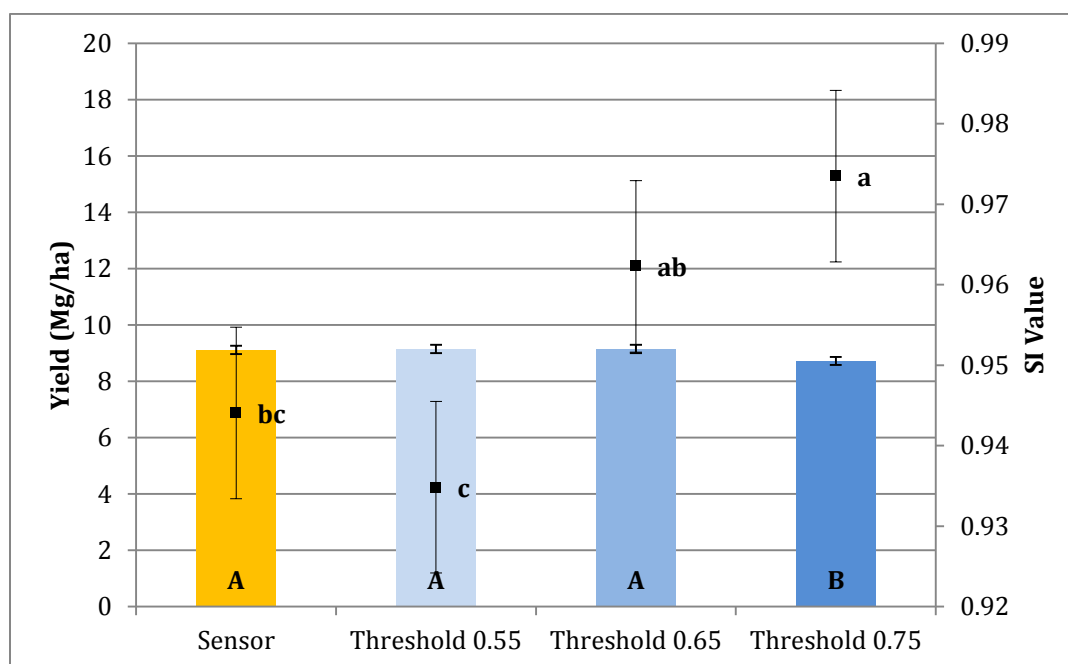


Figure A.5: Whole strip treatment values for 10LE by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

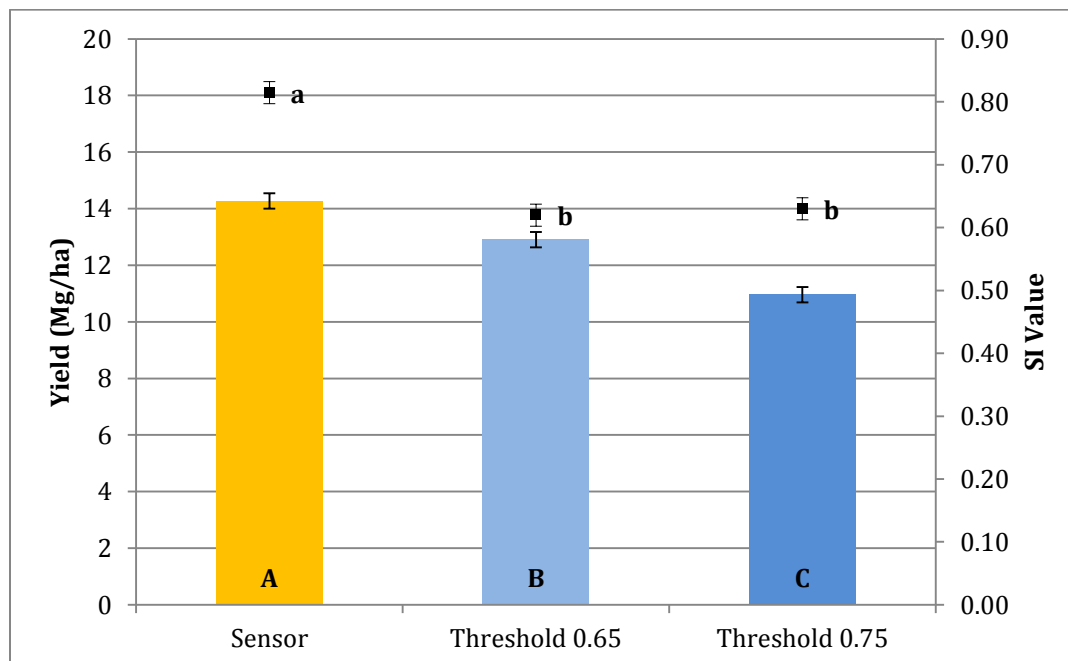


Figure A.6: Combined imposed threshold values for 09RA by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

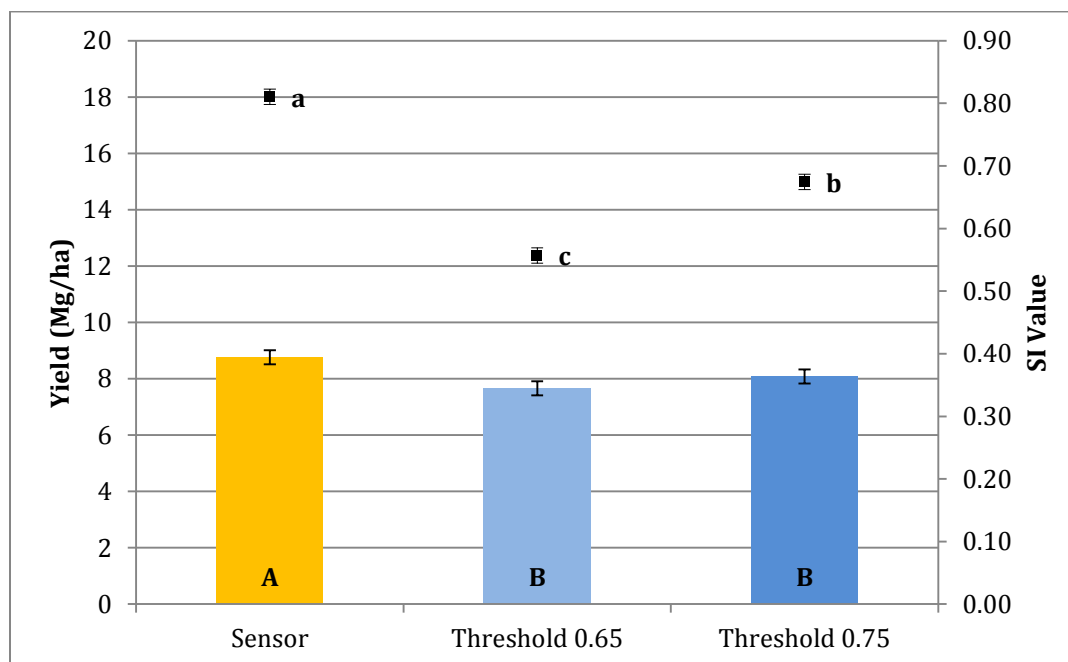


Figure A.7: Combined imposed threshold values for 10LE by treatment for grain yield in bar format on the primary axis. Values by treatment for the SI value at time of sensing (V11) in point format on the secondary axis. Error bars represent the Duncan multiple range test separation value. Means with the same letter are not statistically different ($p=0.05$).

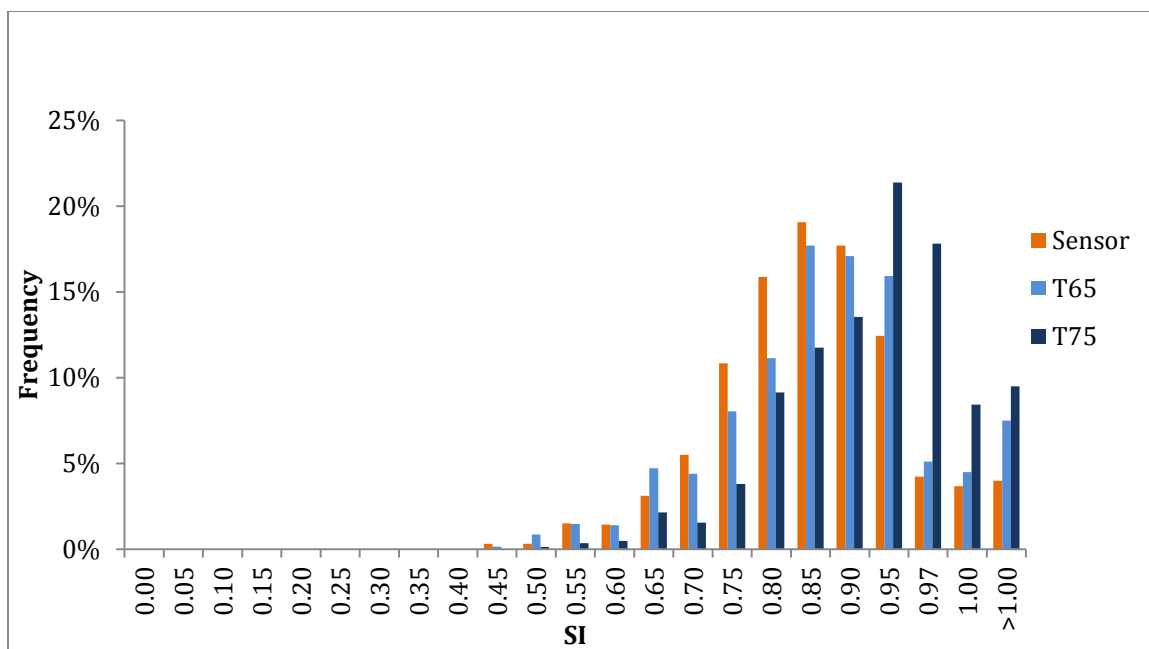


Figure A.8: Distribution of SI values by treatment for 09BR

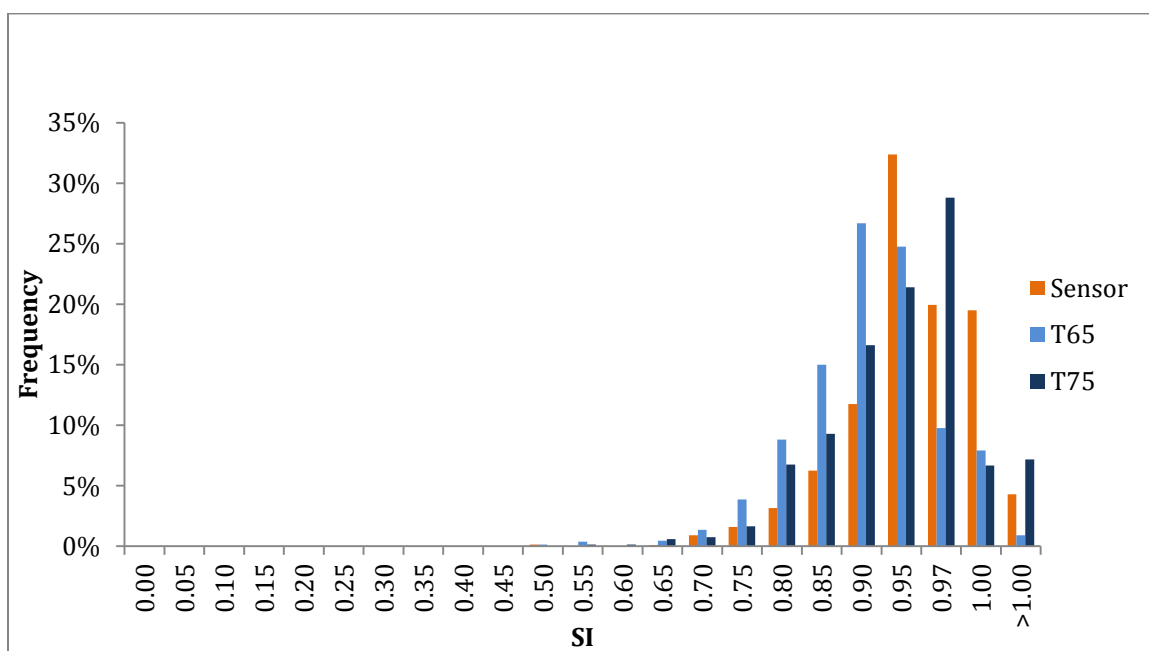


Figure A.9: Distribution of SI values by treatment for 09HU

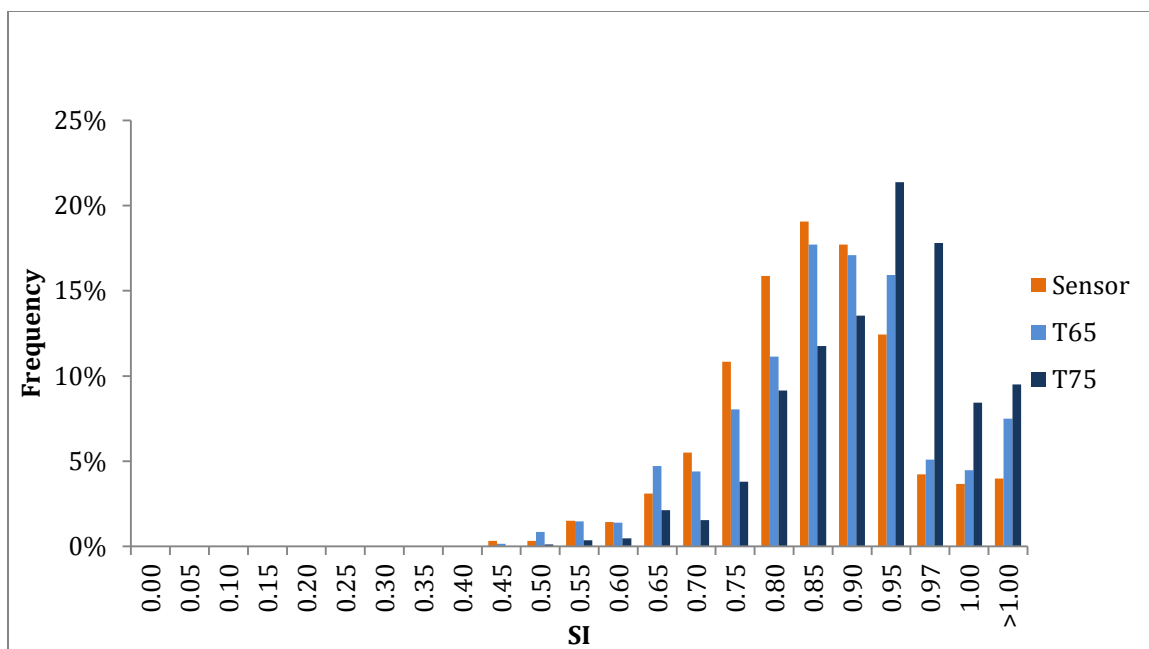


Figure A.10: Distribution of SI values by treatment for 09RA

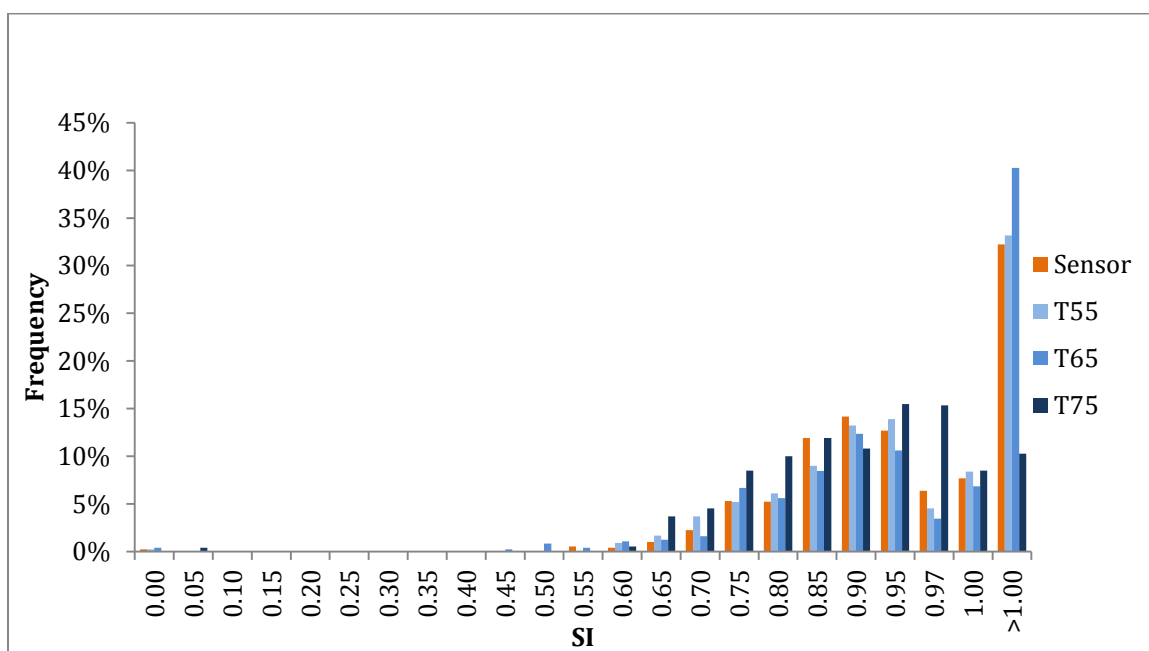


Figure A.11: Distribution of SI values by treatment for 10LE

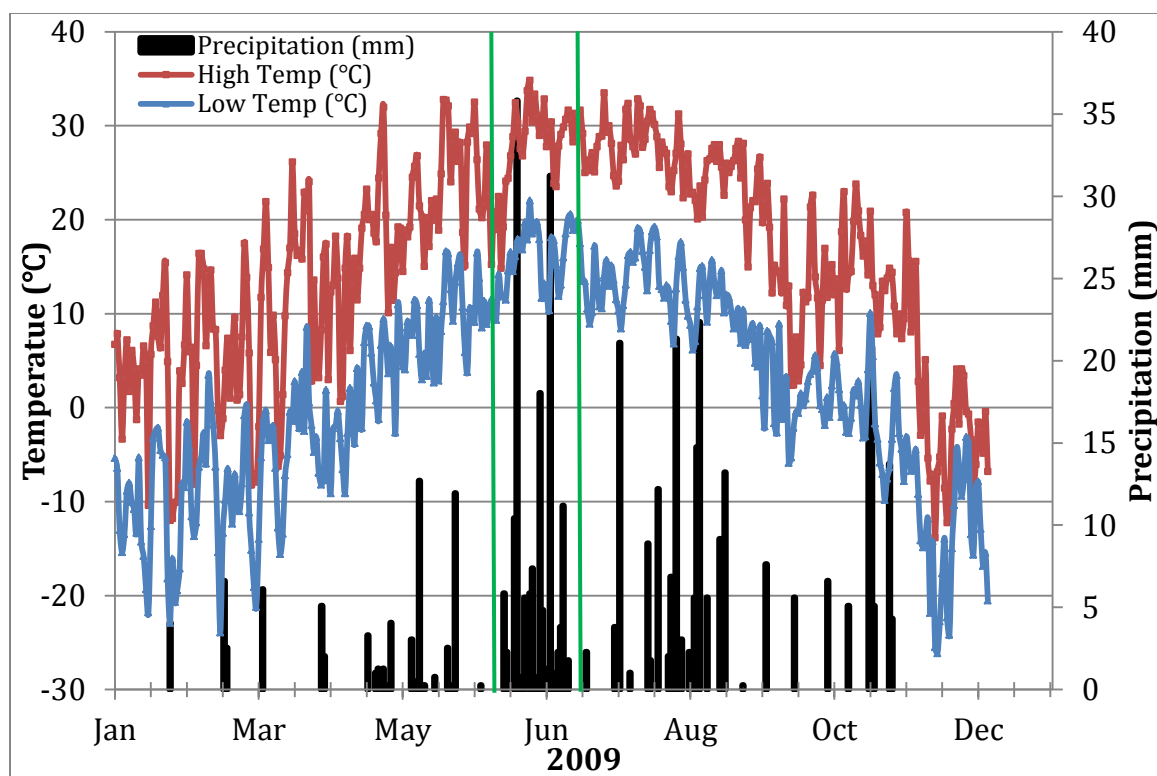


Figure A.12: Site 09BR temperature and precipitation history for 2009. Green lines indicate date of N application.

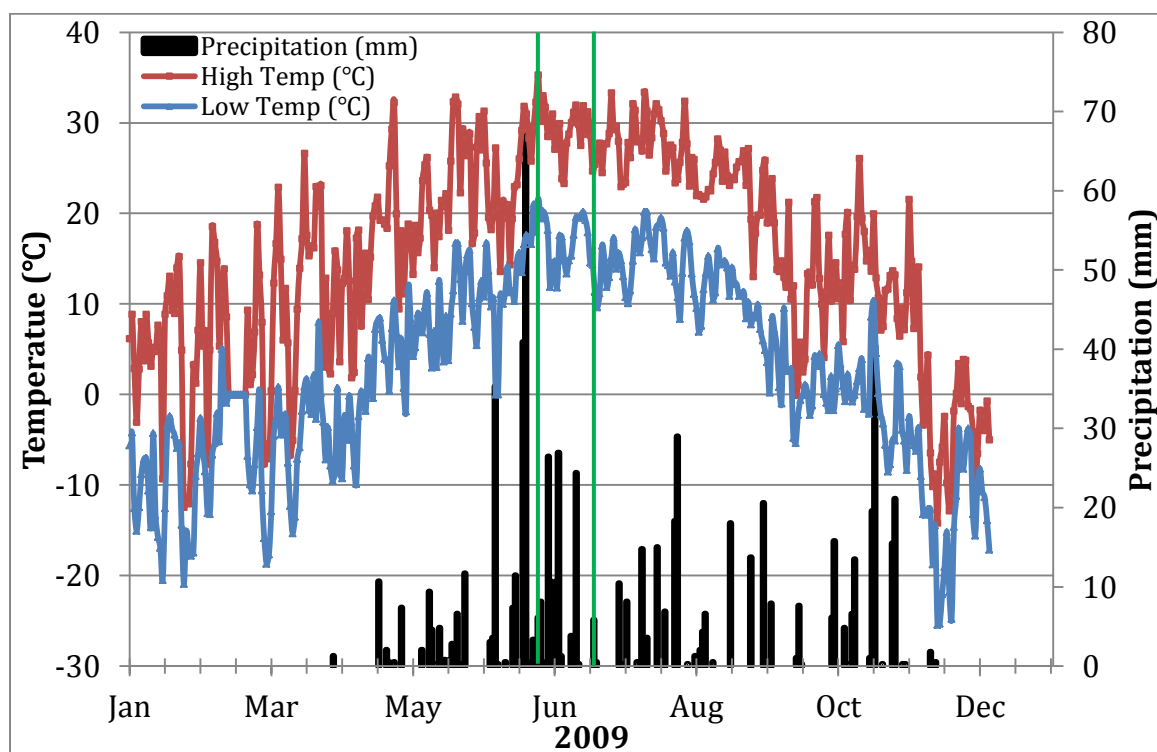


Figure A.13: Site 09HU temperature and precipitation history for 2009. Green lines indicate date of N application.

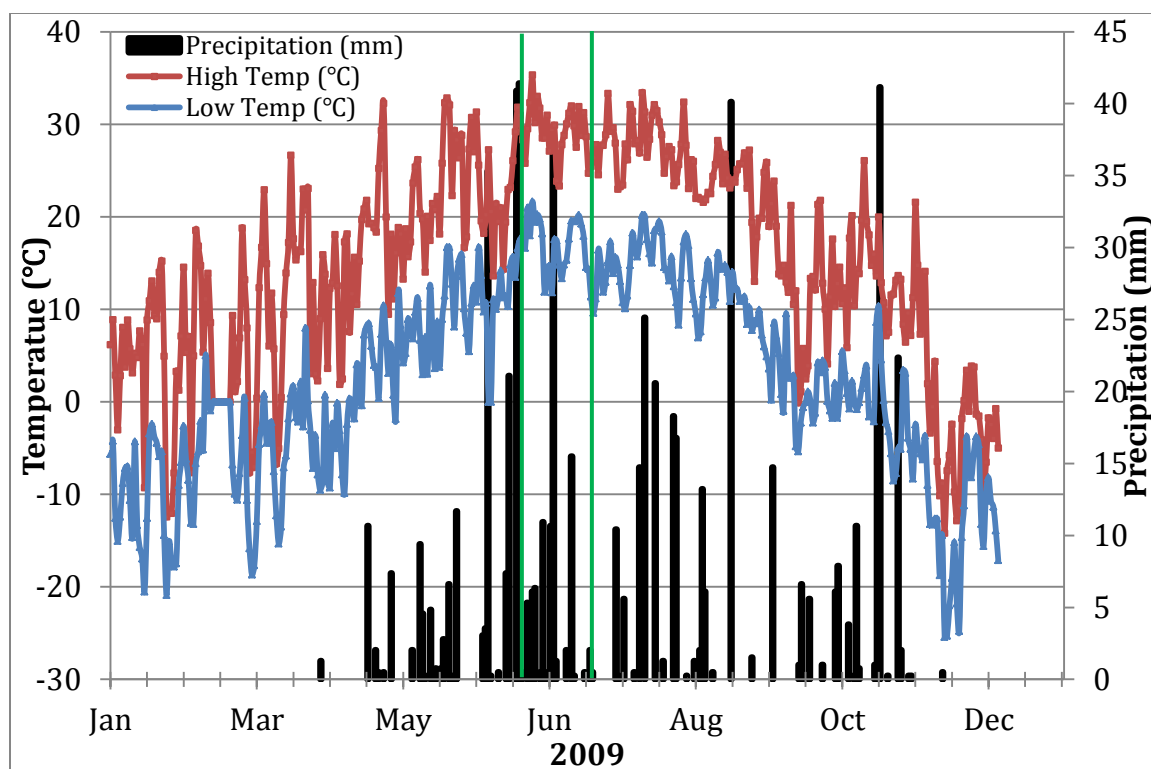


Figure A.14: Site 09RA temperature and precipitation history for 2009. Green lines indicate date of N application.

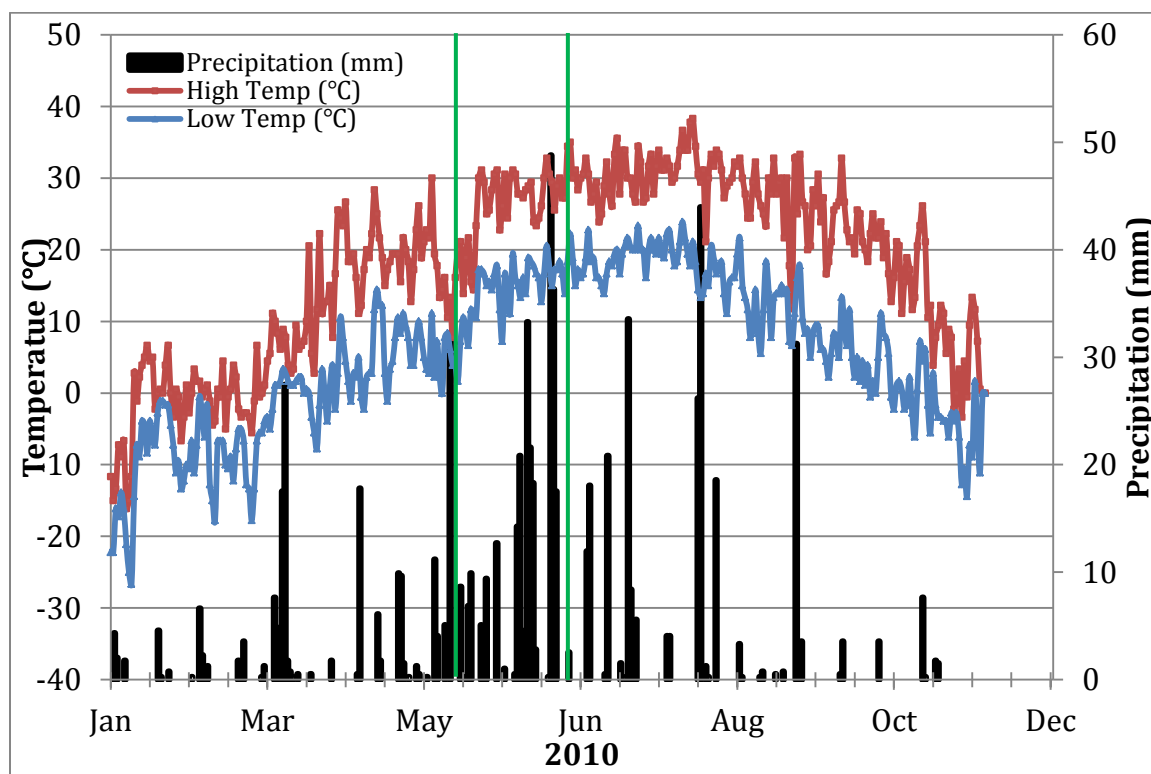


Figure A.15: Site 10HU temperature and precipitation history for 2010. Green lines indicate date of N application.

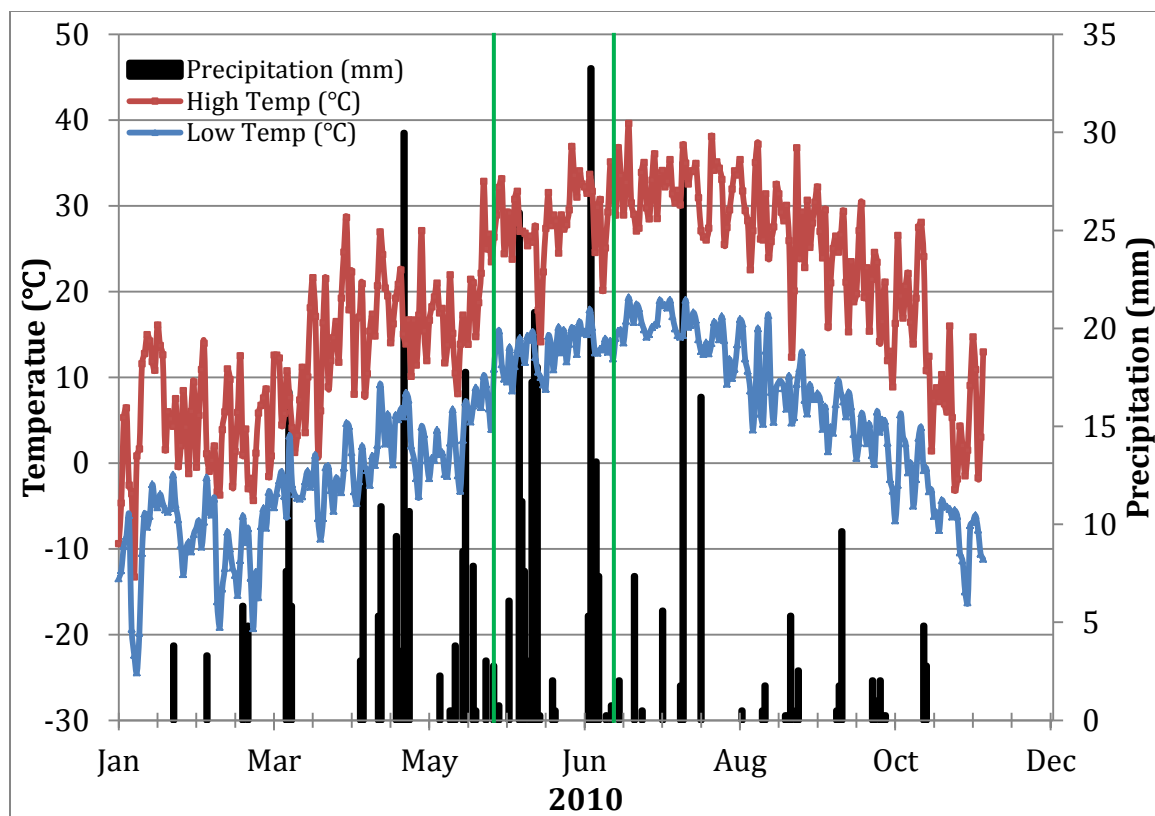


Figure A.16: Site 10LE temperature and precipitation history for 2010. Green lines indicate date of N application.

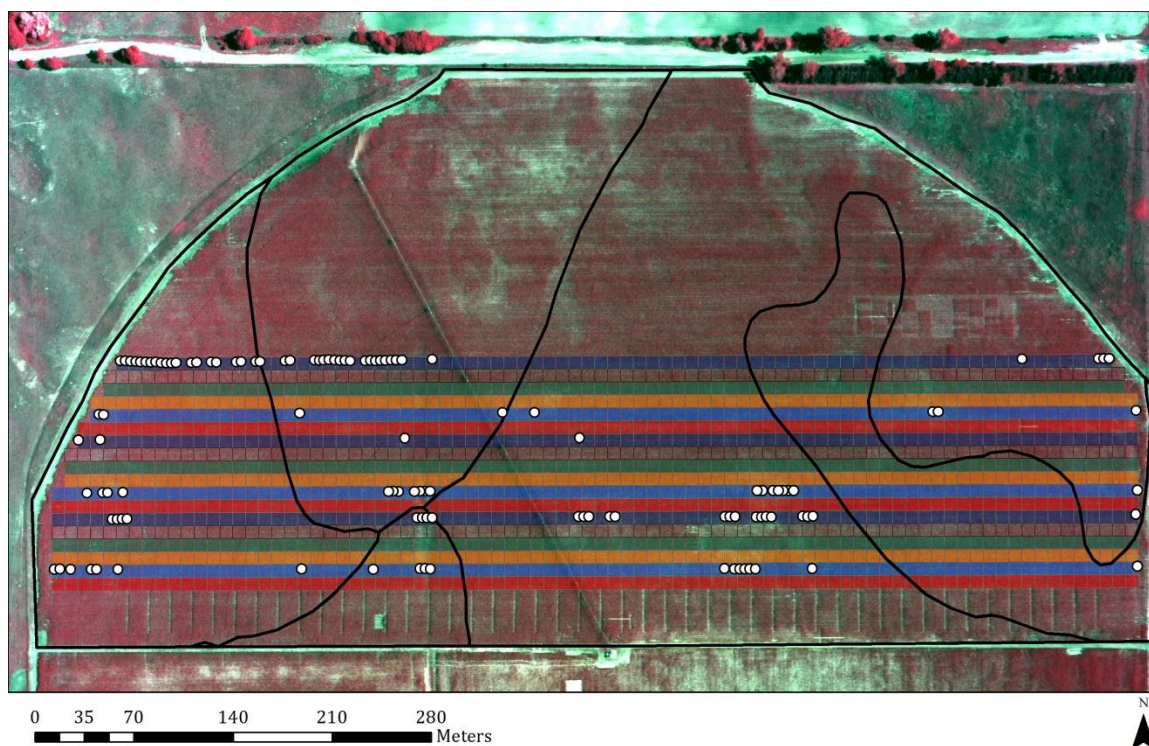


Figure A.17: Spatial occurrence of imposed thresholds for Site 09BR with soil series boundaries overlaid in black.

○ Threshold Imposed

Treatment

- Reference
- UNL
- Sensor
- Threshold .65
- Threshold .75

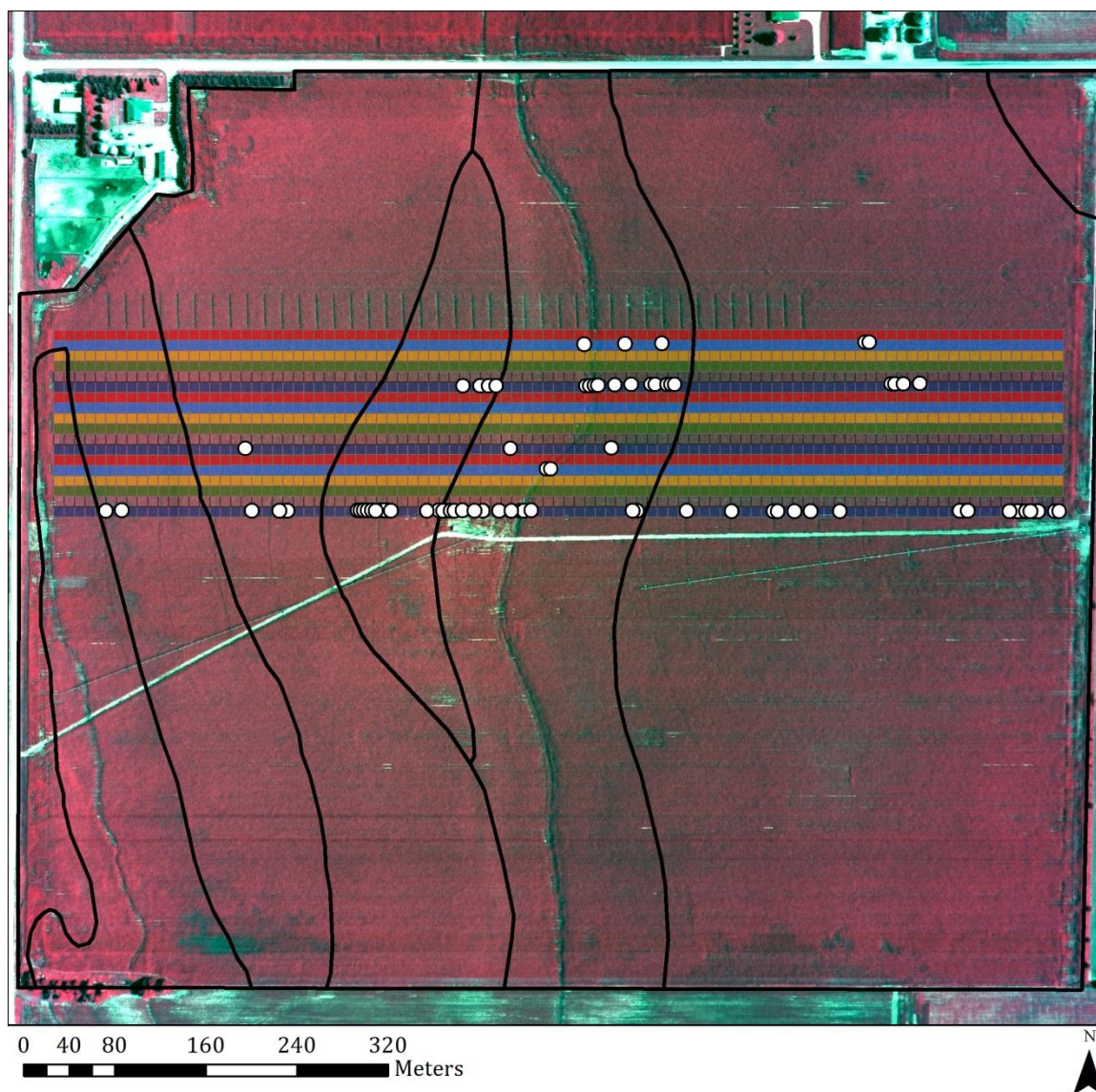
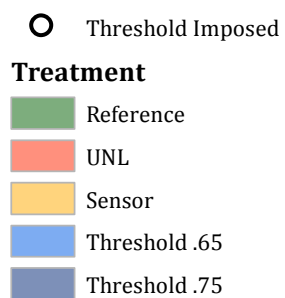


Figure A.18: Spatial occurrence of imposed thresholds for Site 09HU with soil series boundaries overlaid in black.



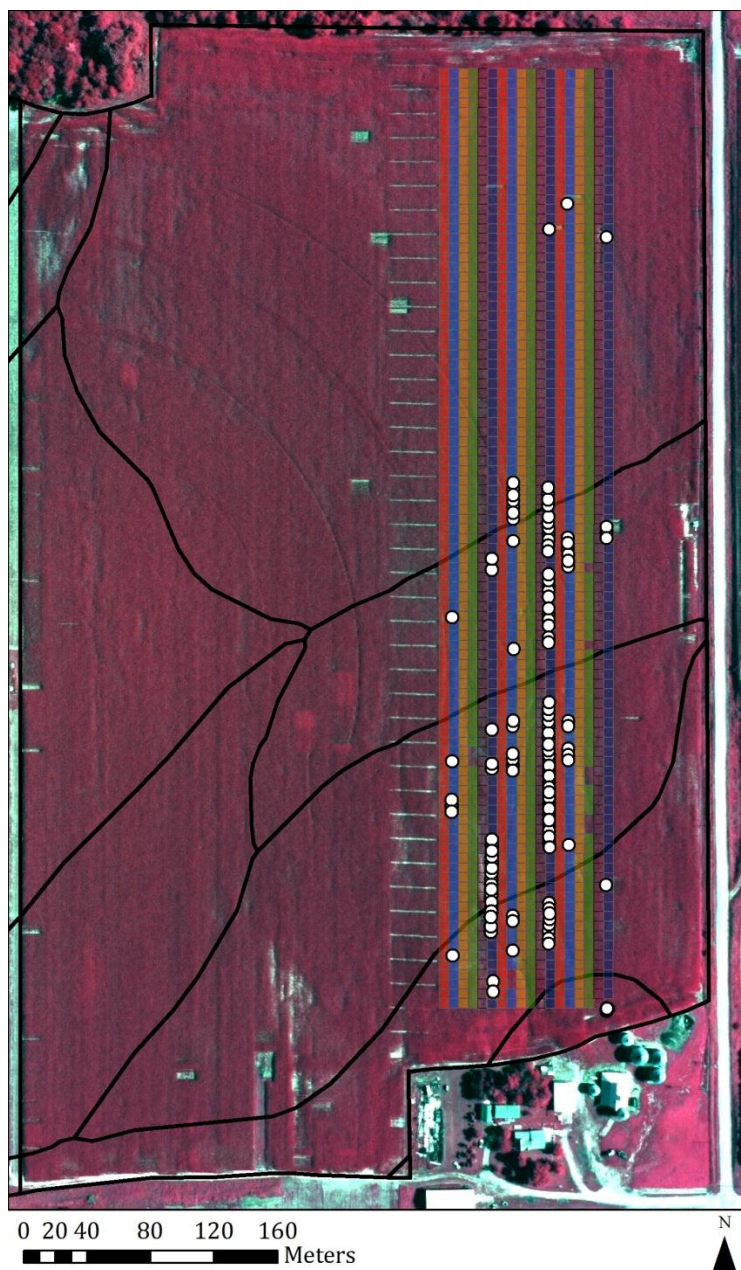
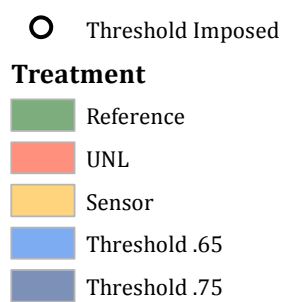


Figure A.19: Spatial occurrence of imposed thresholds for Site 09RA with soil series boundaries overlaid in black.



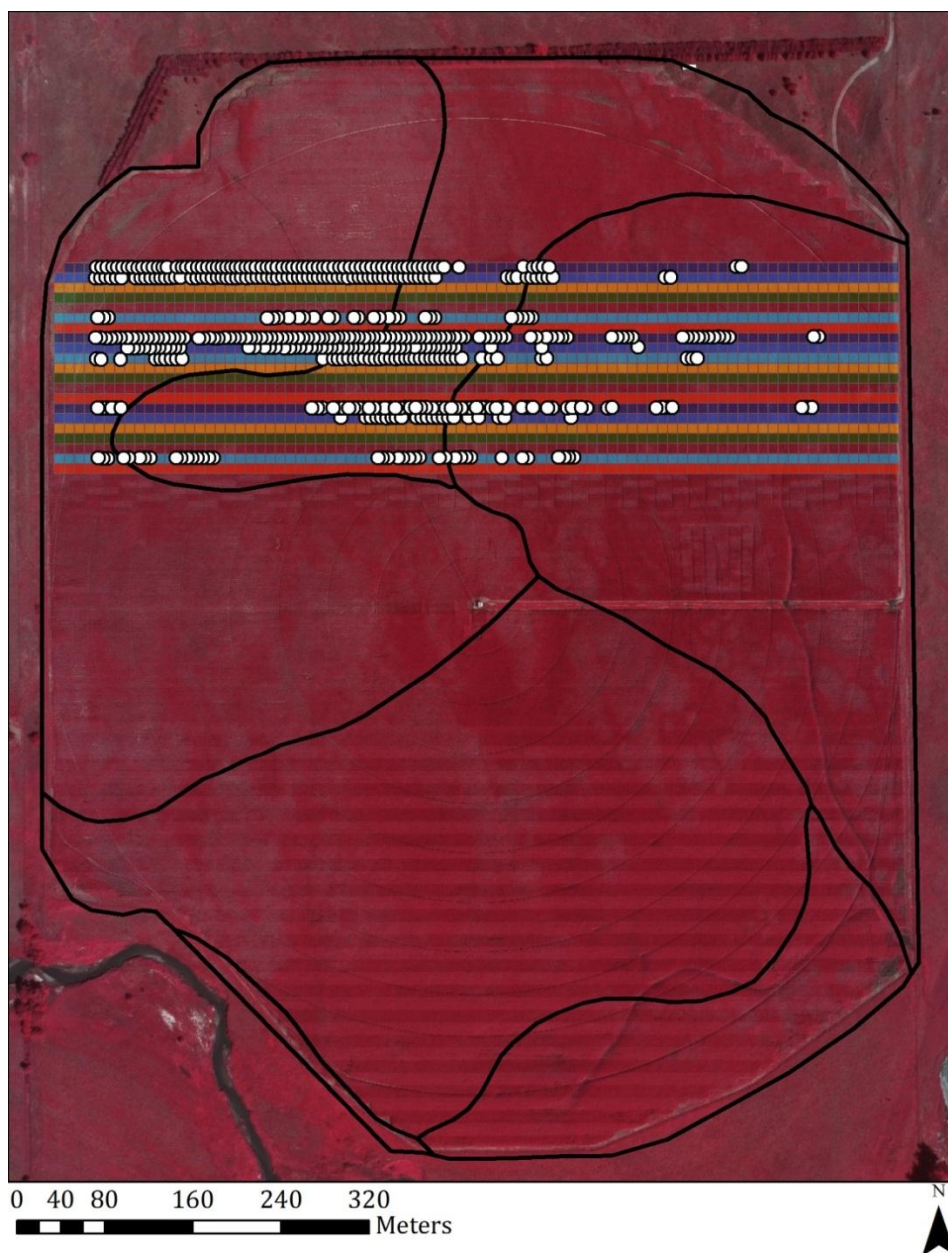


Figure A.20: Spatial occurrence of imposed thresholds for Site 10BR with soil series boundaries overlaid in black.

○ Threshold Imposed

Treatment

- Reference
- UNL
- Sensor
- Threshold .55
- Threshold .65
- Threshold .75



Figure A.21: Spatial occurrence of imposed thresholds for Site 10HU with soil series boundaries overlaid in black

○ Threshold Imposed

Treatment

- Reference
- UNL
- Sensor
- Threshold .55
- Threshold .65
- Threshold .75

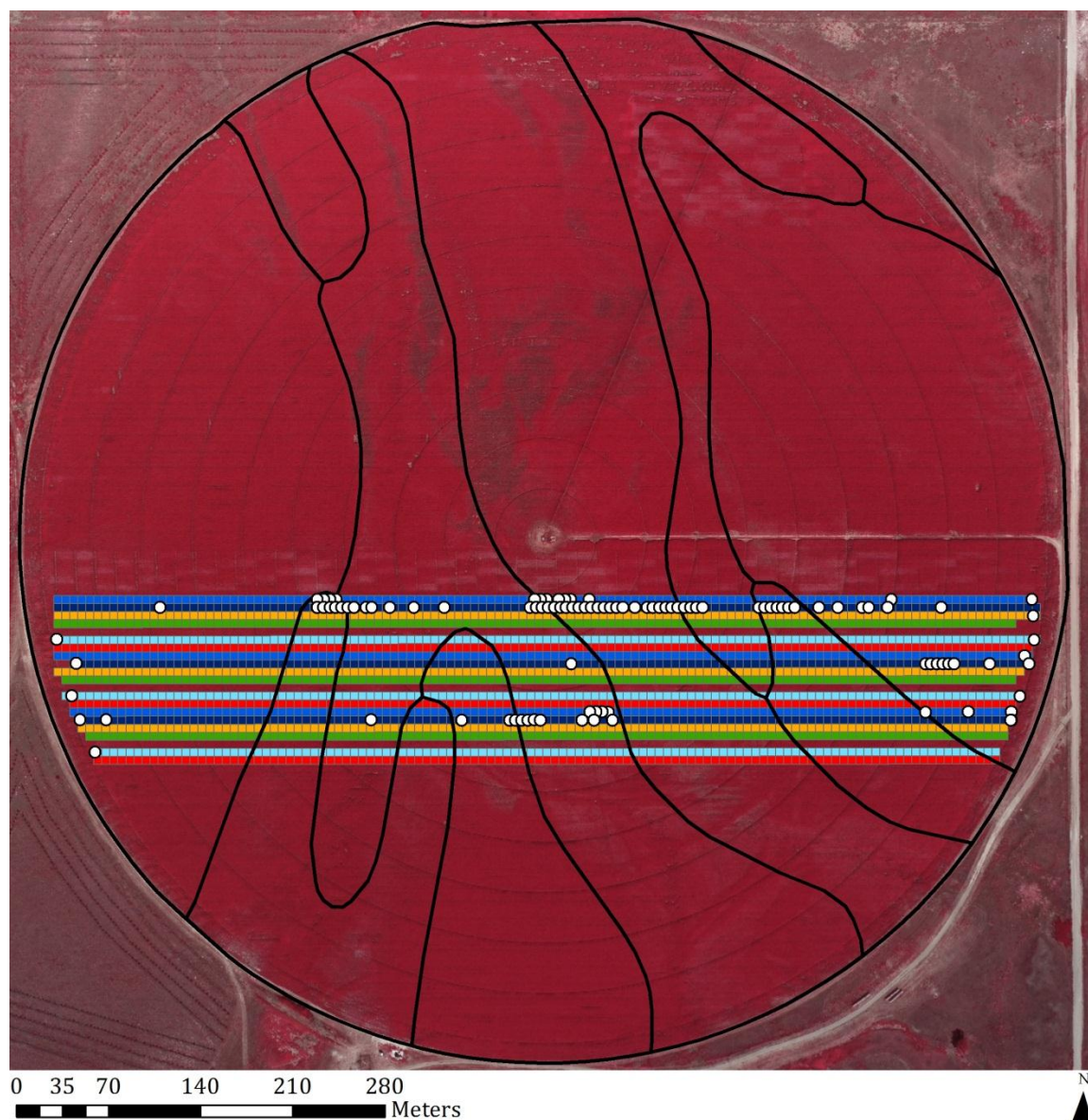


Figure A.22: Spatial occurrence of imposed thresholds for Site 10LE with soil series boundaries overlaid in black..

○ Threshold Imposed

Treatment

- Reference
- UNL
- Sensor
- Threshold .55
- Threshold .65
- Threshold .75